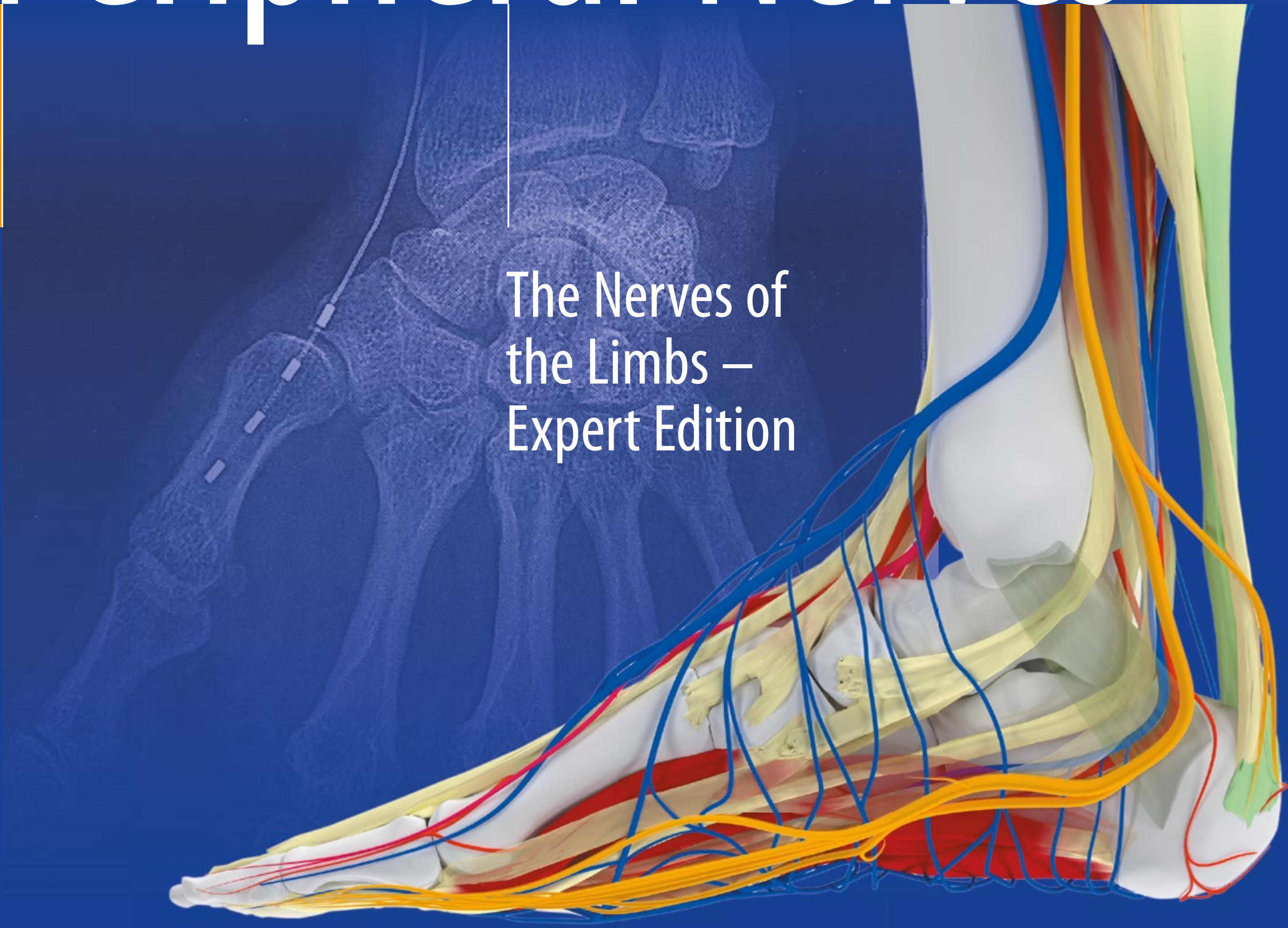
Philippe Rigoard
Editor

Atlas of Anatomy of the Peripheral Nerves



The Nerves of the Limbs – Expert Edition

Springer

ATLAS OF ANATOMY
OF THE PERIPHERAL NERVES

ATLAS OF ANATOMY OF THE PERIPHERAL NERVES

THE NERVES OF THE LIMBS

–

EXPERT EDITION

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Translation from the French language edition ‘Atlas d’Anatomie Des Membres - Nerfs Peripheriques’ by Philippe Rigoard © Elsevier Masson, Issy-les-Moulineaux, 2016; ISBN : 978-2-294-74244-6

ISBN 978-3-030-49178-9 ISBN 978-3-030-49179-6 (eBook)
DOI 10.1007/978-3-030-49179-6

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This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

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Foreword I

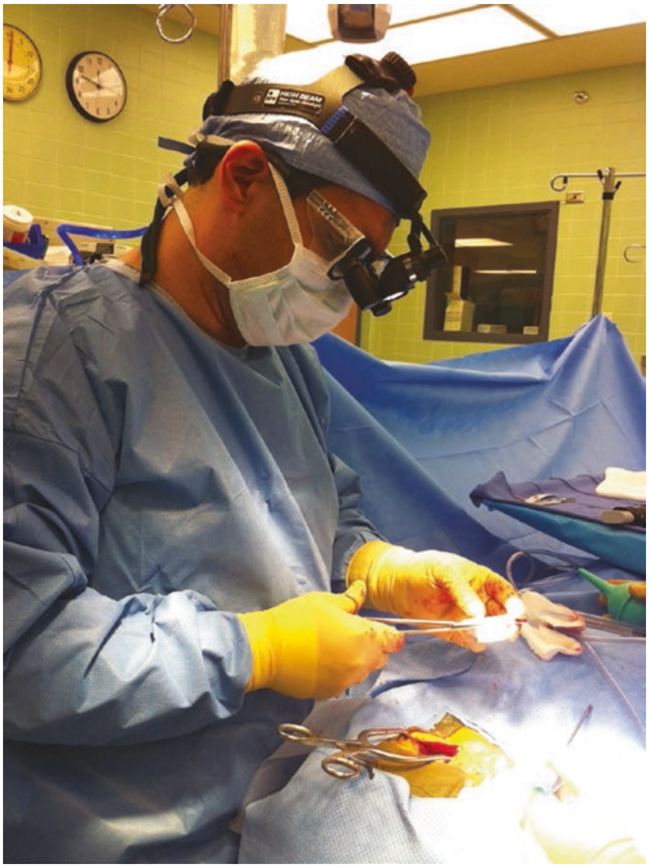
There is no argument that one cannot be a surgeon without detailed knowledge of anatomy. And of all human organs and systems, the anatomy of the nervous system is by far the most complex and most fascinating—something even non-neurosurgeons would probably agree. But the fascination frequently, and reasonably so, focuses on the central nervous system; after all, the anatomy of the brain and spinal cord is inseparable from their function, and the brain functioning makes a person alive. But the peripheral nervous system is what connects the brain and spinal cord with the rest of the body, what carries information to and from it, makes us move and feel, in effect allowing us to function.

When I first heard about Dr. Rigoard's project aimed at creation of comprehensive but user-friendly atlas dedicated to the anatomy of the peripheral nervous system, I was very doubtful that he will be able to pull it through—a prominent and busy practicing neurosurgeon, who, on top of his professional life, is deeply dedicated to his family, is not expected to complete such grandiose task while maintaining a full-time clinical practice. But he proved me wrong—this atlas is a reality and its level surpasses all expectations! A combination of high-quality anatomical drawings with amazing computer graphics and deep understanding of functionality of the peripheral nervous system is the basis of this anatomical masterpiece.

When I discussed the contents of this atlas with its creator, Dr. Rigoard reminded me that there is a concept of dividing the peripheral nervous system into three main components: the cranial system that contains somatic sensory motor, special senses and vegetative part and develops from branchial arches; the axial system that includes prototypic mixed sensory motor nerves, gets derived from metameric spinal branches and also includes vegetative component; and, finally, the so-called exploratory system that focuses on exploration of the surrounding environment and allows one to move around and gather information from outside world using the "extensions" of the trunk called limbs. This volume of the atlas is dedicated to the latter system and is focused on the innervation of limbs starting with dedicated plexuses and continuing with major peripheral nerves.

Anatomy books are the milestones in the development of modern medicine. Just few years ago, we all celebrated 500 year anniversary of the original publication of *The Fabric of the Human Body* by Andreas Vesalius—and that book is alive even now. Reading the Rigoard's atlas of the peripheral nervous system, I could not resist the temptation to compare and contrast these two treatises separated by a half of millennium: the anatomy did not change, and neither did the much-needed attention to detail. What changed is our understanding of function and, most notably, our ability to develop three-dimensional representation of anatomy, and this difference makes this anatomical atlas more practical and more useful.

Merging art and science, Dr. Rigoard and his team succeeded in creating a remarkable teaching tool that will help innumerable medical students and trainees all over the world to better understand peripheral nerves. As a matter of fact, I feel that this atlas will be most beneficial to practicing neurosurgeons and neurologists who can use it to augment their daily practice through improved familiarity with anatomical nuances that explain a multitude of clinical conditions and guide various diagnostic and therapeutic procedures.



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Foreword II

The *Atlas of Anatomy of the Peripheral Nerves* written by Prof. Philippe Rigoard has an innovative approach ranging from anatomy and neurosurgery to medical imaging.

At first glance, one is immediately struck by the modern, rich iconography of this book dedicated to the nerves of the limbs.

Basing their work on real anatomical facts, the author uses computer technology in order to transfer the knowledge necessary for exploration, diagnosis and medical and surgical care.

The study of each nerve is considered in all its aspects: embryology, morphology, physiology, medicine and surgery. All of this is accompanied by new scientific acquisitions.

This work confers great honour to the author and his international team, whose members are all passionate about anatomy, computer science or innovating surgery.

I am firmly convinced that the students following initial or neurosurgery courses will highly benefit from this wonderful pedagogical book dedicated to peripheral nerves.

Pierre Kamina
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Acknowledgements

To Jean-Philippe Giot,
For all the hours spent in front of our computers during the atlas' beginnings, discovering and then trying to familiarize with Blender to infuse my watercolour sketches of classical anatomy with a graphical virtuality and to give them a life in dynamic 3D.

To Monique,
For her exemplary tenacity and generosity she shows day to day for us. For the skill with which she colourized some figures with her left hand and also her kindness for reading the achieved atlas.

To Bénédicte Bouche,
Genuine artist of stimulation. For her unique vision of peripheral nerve stimulation, her genius, her enthusiasm and her sincerity.

To Line Jacques,
For being so generous as to supply us with some pictures of surgical views that correspond to more than 20 years of experience in peripheral nerve regeneration in Canada.

To Maxime,
The ambassador of the international version of this book. His persistence, his devotion and his very linguistic skills have proven to be very useful for making the English version of this atlas come to life. A big thank you.

To Nancy,
For her precious collaboration, her friendship and her taste for adventure.

To Prof. Françoise Lapierre,
Without whom I would never have become a neurosurgeon with a keen interest for anatomy, handicap surgery and peripheral nerves. Her day-to-day accompaniment, trust and kindness have allowed many adjustments and have allowed me to discover myself. She instilled a demanding nature as well as humility in my everyday life. She made me understand that humour could be a resource and a form of wisdom that is worth many other forms of knowledge. She asked me to explore every nook of the unexpected in order to adapt, grow and resist. Finally, more than anyone else, she made me feel the desire to give freely to learning surgeons and anatomists so as to feel accomplished through my students and realize that, ultimately, the goal of teaching is *sharing*.

To Prof. Benoit Bataille,
For the freedom he always bestowed upon me and for his support as a mentor.

To Dr. Bertrand Leriche,
Who uncovered a small part of his talent, taught me and patiently watched me decompress my first carpal tunnels and femoral cutaneous nerves, at the Hospital Centre of Saint Pierre, Island of Reunion, as a father would have. May his benevolence and kindness here be gratified.

To Prof. Konstantin Slavin,
Who welcomed me so warmly in his Department of Neurosurgery in Chicago in summer 2013. Beyond his very impressive surgical skills and worldwide recognized expertise in the neuromodulation field, I discovered a man guided by selfless principles, inspired by art and driven by a peculiar positive energy. He is to be remembered by his students and colleagues alike as one of this century's most brilliant pioneers of neuromodulation. I am honoured for my path to have crossed his and grateful for the moments we shared exploring neurosurgery. I will always remember him as an example and try to follow his steps, as a source of inspiration.

To Prof. Kamina,
Who welcomed me with open arms as soon as I arrived in Poitiers in 2000 and who trusted me from the beginning and suggested that I express my interest for anatomy, right since my first semester of internship in surgery, in the frame of the amphitheatres of the Faculty of Medicine of Poitiers, a chalk in the hand.

To Dr. Dominique Bastian,
My first professor of anatomy, in the Faculty of Medicine of Saints-Pères, Paris, a brilliant mind, marginalized by his avant-garde vision of modern anatomy. An exceptional draughtsman. An artist capable of accommodating us for several years, several times a week, in his office above the rooftops of the Quartier Latin to draw so many memories, paintings and charts on the walls. It was with him that the first step of popularization of the human body allowed me to discover the extent to which humans can be considered so complex and so simple at the same time. It was with him that the vision of a structure prolonged itself in that of an animated body, when he allowed me to walk through the doors of the Gobelins School of Arts or those of the course of morphology in Ecole des Beaux-Arts.

To Prof. Vincent Delmas,
For the trust that he always granted me.

To Prof. Jean-Pierre Richer,
Prof. Jean-Pierre Faure and Dr. Cyril Breque and all the personnel of the anatomy laboratory of the medicine faculty of Poitiers University for their warm welcome. We were able to come and work regardless of the time or circumstances and always be welcome with a smile and great professionalism. Thank you for your sincerity and complicity. Thank you for always being by our side.

To Prof. Remy Guillevin for giving access to his radiology department for my team, as well as all the technicians specialized in medical electroradiology of Poitiers Hospital Centre for their kindness, their availability and their advice.

To the N3Lab:
Bertille, for her meticulous assembly work; this atlas was a revelation. She has truly bewildered us. Manuel, for his faultless availability and his samurai spirit.

Olivier, for his management skill and day-to-day cheerfulness.
For all the students learning neurosurgery or anatomy and those pertaining to the spine department of Poitiers Hospital Centre who worked for the project of this atlas:

Guillaume, Sophie, Eleonore, Enel, Clarisse, Aziz, Justine L, Paul

And particularly to two young and bright learning anatomists, Justine Bardin and Romain David, who managed to find the strength and courage to dive, like two conquerors, in this anatomical atlas, whilst still studying medicine and to sublimate their watercoloured works to the highest degree to make this book unique and contemporary. May their passion of "beautiful and well-done work" be rewarded with a career as bright as they deserve.

Romain, this adventure has brought you to a revelation and has progressively propelled you from "second in command" to "navy captain". I hope that this paternal inspiration will help you navigate across the most beautiful seas of the human anatomy, quench your thirst of discovery and go on a quest, in your turn, to find "'seconds' in command" that will deserve the way you share your passion and inspiration. You will then be rewarded for all the sacrifices that made you a wonderful project manager and a fellow traveller without equal.
May you hereby be gratified.

To Kevin Nivole,
For his exceptional investment in the graphical and computing conception of the atlas. We made a great anatomist of you! This atlas owes you a lot.

To Nathalie L'Horset-Poulain, Nathalie Huilleret and the publishing house Springer, for the trust they granted us and the allure of this relationship. May this book be the first of a long and beautiful collaboration.

To my family, my parents, my step-parents, and my brother.

To Nathy, Manoé, and Orion,

The two sunshines and the illuminated sky of my life, who brighten my vision on so many things.
I dedicate this atlas to you, as the result of intense labour and many compromises, so that it seals a chapter, a time of our lives, at the end of which so many expectations and dreams, far from work and books, must now be satisfied. Thank you for respecting my passion for all these years and, above anything else, believing with such intensity in our love.

The hanging gardens

Philippe Rigoard,
New Caledonia, December 2015

Painting inspired from the tropical plants and flowers of Monique and Jean-Pierre Le Leizour's garden
Acrylic paint, oil, cardboard, personal photographs, watercolour, charcoals and felts

Preamble

PHILOSOPHICAL APPROACH OF AN ANATOMICAL GARDEN

Choses simples.
Choses épurées de tout environnement artificiel, carcan sociétal, construits par l'Homme.
La connexion avec la Terre.
La Vie.

Simple things
Free from artificial constructs made by Humans.
Connection to Earth.
Life.

Poitou-Charentes, 2019

This enchanting garden will exhilarate our senses, offering us its multicoloured palette, and it will distil its spices reminding us that it is nature itself, as opposed to the artificial elaboration of the mind, and that it is the opposite order to the well-reasoned, the unconscious against the constructed.

Trying to decompose the morphology of a garden without altering it completely, in order to measure its beauty and savour its meanders a little more, corresponds to the challenge of producing an anatomy atlas that is intended as innovative.

The quest of this garden is the anatomical journey that is given to you in this book. It is a journey along collateral arteries and muscle frameworks, a journey at the core of the human body.

Anatomy is a science applied to medicine; it is a living discipline, a day-to-day reality. In the way that anatomy is currently taught to students, the proliferation of teaching materials and platforms is too often privileged as well as the literary and theoretical character, even though this teaching should primarily be visual and tactile. Where the main subjects are curvatures and reverse curvatures, it should be possible to learn how to draw them and how to feel them.

What is the use of anatomy?

Anatomy, from its morphological approach, starts straight at the physiological, radiological and even semiological knowledge. It is anatomy that allows a young student in medicine to learn the distinction between "normal" and "pathological". From its surgical approach, anatomy will then guide the novice as the confirmed surgeon to highlight one structure or another to realize an approach they are not used to. The anatomical basics should seal the medical skill and help the (future) doctor to build up his knowledge of mankind.

The teaching of anatomy must remain simple and, in the end, rather popular. The human body is a living painting.

It should focus on the progressive development of a figurative GPS* in the head of an individual and, this way, use the technological tools at our disposal nowadays, converting surface into volume, a paper sheet into layers and textures. This has led us to offer an atlas defined in three dimensions.

This atlas has been conceived in an atypical and unique way to correspond, in a manner of speaking, to an illustrated logbook, just like what a young companion may gather along his medical formation.

Philippe Rigoard
Editor

*GPS: global positioning system

> "The hanging gardens,
> They are the ideal perpetually sought and fleeting of an artist,
> They are the inaccessible and inviolable refuge…."
>
> Jehan Alain, poet, organist and composer (1911–1940)

About This Book

It was in 2007 that the idea of an atlas of anatomy of peripheral nerves had germinated in the mind of Prof. Philippe Rigoard, an aficionado of drawing and anatomy since his beginnings.

Initially constituted of a collection of sketches, then watercolours, the computer technology has then made it richer thanks to Dr. Jean-Philippe Giot, his accomplice in medicine studies, and also thanks to an original approach using the 3D computer graphics software “Blender”.

The use of this 3D tool has brought a whole new dimension to these sketches. The chroma keying of the nerve and vascular paths in overprint of the watercolours has first and foremost highlighted the important structures on the original anatomical sketches. Furthermore, the use of alpha and texture blending has exacerbated the notions of “superficial” and “deep” amongst tissues. The aim was therefore to provide a new perspective on classic and surgical anatomy views.

This “companion guide for apprentice surgeon” used to be meant for a young audience. It was in the continuation of this line of thought that the first watercolours, revisited with chroma keying, were published in 2009 in the *Neurochirurgie* medical journal in order to illustrate the most common surgical approaches of peripheral nerves.

Since 2010, fresh, strong energies have converged towards this project, and the new hired collaborators have not only enhanced it but also revisited and completely transformed it, giving it its current shape. This has been possible especially thanks to the implication of Mr. Kevin Nivole, a competent, freshly graduated computer engineer, to whom we owe the partnership with the Japanese team of Dr. Kousaku Okubo whom we would like to show our appreciation to. This collaboration has enabled us to access a morphological database (BodyParts3D, concept label for FMA*) and to use it in order to conceive the raw material for a genuine 3D anatomy atlas over a few years: a patiently worked-on prototype, structure after structure, texture after texture and curve after curve.

In the end, since the beginning of 2013, this atlas features perfectly keyed, realistic and original structures of bones, muscles and viscera. After two more years of hard work, Kevin Nivole’s undeterred passion led to de novo development of vascular and nerve elements in human limbs, as well as an ultimate level of refinement of the textures of every featured structure: bone, tendon, muscle, etc. At this point, the team discussed about reflections, roughness, clarity, gloss, elasticity and even gleaming effects. Team interactions bloom, language evolves, and the renders prove to be more and more surprising each time.

This is how the transition to 3D graphics became possible and led to the production of authentic 3D views.

Following the development of this tool, the team discerned an incredible range of possibilities, as the 3D environment enabled the capacity of trying out an infinite number of anatomical views as well as many angles of attack for its pictures. It progressively showed us the human body’s nerves in a unique way and imprinted indelibly their intimate relations with all the other structures in our memories to the smallest detail. It is this enthusiasm that we wished to share with the reader and that made us give a central place to illustrations in this atlas, majorly supporting the descriptions through its sheer visual impact. Each illustrated chart is therefore composed of several figures and created whilst keeping in mind the possibility for it to be read independently, nearly without need to read through the text. As a second step, we elected to produce it under a written form but using a fully corresponding double-page disposition in order to be as comprehensive as possible and to be able to give satisfaction to the seasoned reader. In most cases, the anatomical structure presentation will be under the shape of a “plane per plane” dissection. However, the use of alpha blending has favoured their revealing in layers called “muscle layers” or “neurovascular layers”.

The leading concept was to apprehend space differently.

Students, as staunch supporters of learning by heart, sometimes victims of an ill-adapted “over-education”, will therefore be able to build their own vision of space: a keystone of anatomical comprehension. Passionate and competent anatomists will enjoy strolling through this atlas, sharpening their knowledge or learning information again. There lies the reason why we mentioned the idea of a GPS in the philosophical preamble of this book.

To conclude this brief glimpse, this anatomy tool is a product of time, constantly evolving. Therefore, the reader will not be surprised by the diversity, the succession and the combination of teaching materials. We wish for this atlas to become a suitable complement for student and professional individuals who would enjoy to immerse themselves in the scenery of peripheral nerves as though to abandon themselves in it or better yet as though to find themselves.

We wish you a pleasant anatomical journey!

Romain David
Project Manager and Co-author

*License Bodyparts3D	https://creativecommons.org/licenses/by-sa/2.1/jp/
BodyParts3D website	http://lifesciencedb.jp/bp3d

Abbreviations and Nerve Colour Code

Nerves of the Upper Limb	The Axillary Nerve	Ax
	The Musculocutaneous Nerve	MC
	The Radial Nerve	R
	The Median Nerve	M
	The Ulnar Nerve	U
	The Suprascapular Nerve	SSc
	The Long Thoracic Nerve	LT
Nerves of the Lower Limb	The Obturator Nerve	O
	The Femoral Nerve	F
	The Sciatic Nerve	Sc
	The Tibial Nerve	T
	The Common Fibular Nerve	Fi
	The Lateral Femoral Cutaneous Nerve	LFc
	Other Nerves	IH & II

Contents

Part I Morphological and Functional Anatomy of the Peripheral Nerve

The Normal Nerve . . . 2
Morpho-Functional Anatomy . . . 2
  General Organization of the Peripheral Nerve . . . 2
  The Structure and Physiology of the Nerves . . . 4
    Axon . . . 4
    Cytoskeleton . . . 4
    Axonal Flow . . . 4
  Schwann Cell and Myelination . . . 6
  Mechanical Properties of the Nerves . . . 7
  Vascularization of the Peripheral Nerves . . . 8
  Neuromuscular Junction and Transmission . . . 10
  Main Mechanisms of Synaptic Formation . . . 12

The Injured Nerve . . . 14
Physiology of the Damaged Nerve . . . 14
  Pathophysiological Mechanisms . . . 14
Nerve Degeneration . . . 16
Mechanisms of Neural Repair . . . 18
  Axonal Sprouting . . . 18
  Neurotrophic Factors . . . 20
  Potential Functional Consequences . . . 20
  Functional Regeneration . . . 20
  Neuroplasticity . . . 20
Conclusion . . . 21
Bibliography . . . 22

The Plexus . . . 24
Data Learned from Embryology . . . 24
  Embryological Development of the Peripheral Nerves . . . 24
  Growth of Precursor Cells . . . 24
  Development of Segmental Spinal Nerves . . . 24
    Basal Lamina and Alar Lamina . . . 24
    Peripheral Nerve Pathways . . . 24
    Formation of the Myelin Sheath . . . 24
Development of the Innervation of Limbs . . . 26
  Introduction . . . 26
  Notion of Motor Innervation . . . 26
  Notion of Cutaneous Innervation . . . 26
Innervation of the Limbs in Adults . . . 28
  Origin and Constitution of the Limb Nerves . . . 28
The Notion of Plexus . . . 32
Bibliography . . . 34

Part II Nerves of the Upper Limb

The Brachial Plexus 40
The Brachial Plexus 40
Morphological Data 40
The Brachial Plexus Relations 42
  At the Supraclavicular Level 42
  At the Infraclavicular Level 44
Morphological Data: Sono Anatomy 48
Interventional Procedure 54
  Neurostimulation of the Brachial Plexus 54
  Interscalenic Track 54
    Installation 54
    Equipment and Location 54
    Procedure 56
  Supraclavicular Pathway 58
    Installation 58
    Equipment and Location 58
    Procedure 58
Bibliography 60

The Axillary Nerve 62
Peripheral Branches 62
Morphological Data 66
  Origin 66
  Path 66
  Neurovascular Relations 66
  Collateral Branches 66
  Terminal Branches 66
  Motor Function 74
  Sensitive Function 74
  Anastomoses 74
Pathology 76
  Aetiology 76
  Clinical Significance 76
  Clinical Forms 76
  Explorations 76
  Treatment 76
Morphological Data: Sono Anatomy 78
  Installation 78
  Equipment and Ultrasound Tracking 78
  Ultrasound Procedure 78
Interventional Procedure 82
  Infiltration/Block Test 82
    Indication 82
  Out-of-Plane Technique 82
  In-Plane Technology 82

  Peripheral Nerve Stimulation 82
Surgical Procedure 84
  Surgical Indications. 84
  Surgical Approaches 84
    Skin Incision 84
    Nervous Exposure. 84
    Technical Pitfalls 84

The Musculocutaneous Nerve 88
Morphological Data 88
  Origin 88
  Path 88
  Neurovascular Relations 88
  Collateral Branches 94
  Terminal Branches 94
  Motor Function 94
  Sensitive Function. 94
  Anastomoses 94
Pathology 103
  Aetiology. 103
  Clinical Signs 103
  Explorations 103
  Treatment 103
Morphological Data: Sono Anatomy 106
  Installation. 106
  Equipment and Location 106
  Ultrasound Procedure 106
Interventional Procedure 112
  Infiltration/Test Block 112
    Indication 112
    In-Plane Technology 112
  Peripheral Nerve Stimulation (PNS). 112
Surgical Procedure 114
  Surgical Indications. 114
  Surgical Approaches 114
    Skin Incision 114
    Nervous Exposure. 114
  Technical Pitfalls 114

The Radial Nerve 118
Morphological Data 118
  Origin 118
  Path 118
  Neurovascular Relations 118
  Collateral Branches 124
  Terminal Branches 124
  Motor Function 124

  Sensitive Function 128
  Anastomoses 128
Pathology 134
  Posterior Interosseous Nerve Syndrome 134
  Aetiology 134
  Clinical Signs 134
  Clinical Forms 134
  Explorations 134
  Treatment 134
Interventional Procedure 144
  PNS 144
Surgical Procedure 146
  Surgical Indications 146
  Surgical Approaches 146
    On the Arm 146
    At the Elbow 148
  Technical Pitfalls 148

The Median Nerve 152
Morphological Data 152
  Origin 152
  Path 152
  Neurovascular Relations 152
  Collateral Branches 162
  Terminal Branches 162
  Motor Function 162
  Sensitive Function 162
  Anastomoses 162
Pathology 172
  Anterior Interosseous Nerve Syndrome 172
  Aetiology 172
  Clinical Significance 172
  Explorations 172
  Treatment 172
  Carpal Tunnel Syndrome 172
  Clinical Signs 174
    Anatomical Atypias 174
    Clinical Atypias 174
  Differential Diagnosis 174
  Treatment 174
Morphological Data: Sono Anatomy 176
  Installation 176
  Equipment and Location 176
  Ultrasound Procedure 176

Interventional Procedure . . . 180
  PNS . . . 180
Ultrasound Pathology . . . 182
Surgical Procedure . . . 184
  Surgical Approaches . . . 184
    Skin Incision . . . 184
    On the Arm . . . 184
    At the Elbow . . . 184
    At the Forearm . . . 186
    By Hand . . . 188
  Technical Pitfalls . . . 188
Surgical Pathology . . . 190
Electronic Supplementary Material . . . 152

The Ulnar Nerve . . . 194
Morphological Data . . . 194
  Origin . . . 194
  Path . . . 194
  Neurovascular Relations . . . 204
  Collateral Branches . . . 204
  Terminal Branches . . . 204
  Motor Function . . . 204
  Sensitive Function . . . 204
  Anastomoses . . . 204
Pathology . . . 214
  Cubital Tunnel Syndrome . . . 214
  Aetiology . . . 214
  Clinical Significance . . . 214
  Clinical Forms . . . 214
  Explorations . . . 214
  Treatment . . . 216
  Ulnar Tunnel Syndrome (Guyon’s Canal) . . . 216
  Aetiology . . . 216
  Clinical Signs . . . 216
  Clinical Forms . . . 216
  Explorations . . . 216
  Treatment . . . 216
Morphological Data: Sono Anatomy . . . 218
  Installation . . . 218
  Equipment and Location . . . 218
  Ultrasound Procedure . . . 218
Interventional Procedure . . . 230
  Anaesthetic Block of the Ulnar Nerve in the Elbow (Figure U34a) . . . 230
  Anaesthetic Block of the Ulnar Nerve in the Ulnar Canal (Figure U34b) . . . 230
  Ulnar Nerve PNS . . . 232
Surgical Procedure . . . 234

- Surgical Approaches . . . 234
    - On the Arm . . . 234
    - At the Elbow . . . 234
    - At the Forearm . . . 236
- Technical Pitfalls . . . 236
    - By Hand . . . 238
- Main Technical Trap . . . 238

The Suprascapular Nerve . . . 242
- Morphological Data . . . 242
    - Origin . . . 242
    - Path . . . 242
    - Neurovascular Relations . . . 242
    - Collateral Branches . . . 242
    - Terminal Branches . . . 242
    - Motor Function . . . 242
- Pathologies . . . 245
    - Aetiology . . . 245
    - Clinical Significance . . . 245
    - Explorations . . . 245
- Treatment . . . 245
- Morphological Data: Sono Anatomy . . . 248
    - Installation . . . 248
    - Equipment and Location . . . 248
    - Ultrasound Procedure . . . 248
- Interventional Procedure . . . 250
    - Infiltration/Test Block . . . 250
    - RFP . . . 250
    - PNS . . . 250
- Surgical Procedure . . . 252
    - Surgical Approaches . . . 252
        - Skin Incision . . . 252
        - Nervous Exposure . . . 252

The Long Thoracic Nerve . . . 254
- Morphological Data . . . 254
    - Origin . . . 254
    - Path . . . 254
    - Neurovascular Relations . . . 254
    - Terminal Branches . . . 254
    - Motor Function . . . 254
- Pathologies . . . 257
    - Aetiology . . . 257
    - Clinical Significance . . . 257
    - Treatment . . . 257
- Bibliography . . . 259

Part III Nerves of the Lower Limb

The Lumbosacral Plexus . . . 266
Morphological Data . . . 266
  The Lumbar Plexus . . . 266
  The Sacral Plexus . . . 268

The Obturator Nerve . . . 280
Peripheral Branches . . . 276
Morphological Data . . . 280
  Origin . . . 280
  Path . . . 280
Neurovascular Relations . . . 280
  Collateral Branches . . . 288
  Terminal Branches . . . 288
  Motor Function . . . 288
  Sensitive Function . . . 288
  Anastomoses . . . 288
Pathology . . . 294
  Obturator Neuralgia . . . 294
  Aetiology . . . 294
  Clinical Significance . . . 294
  Explorations . . . 294
  Treatment . . . 294
Morphological Data: Sono Anatomy . . . 296
  Installation . . . 296
  Equipment and Location . . . 296
  Ultrasound Procedure . . . 296
Interventional Procedure . . . 300
  Infiltration/Test Block . . . 300
    Indication . . . 300
    Technique . . . 300
    PNS . . . 300
    RFP . . . 300
Surgical Procedure . . . 302
  Surgical Indications . . . 302
    Skin Incision . . . 302
    Nervous Exposure . . . 302
  Technical Pitfalls . . . 302

The Femoral Nerve . . . 308
Morphological Data . . . 308
  Origin . . . 308
  Path . . . 308
  Neurovascular Relations . . . 308
  Collateral Branches . . . 308
  Terminal Branches . . . 314

    - Motor Function . . . 314
    - Sensitive Function . . . 314
    - Anastomoses . . . 314
- Pathology . . . 320
    - Femoral Nerve Syndrome or Femoral Neuralgia . . . 320
    - Aetiology . . . 320
    - Clinical Significance . . . 320
    - Explorations . . . 320
    - Treatment . . . 320
- Morphological Data: Sono Anatomy . . . 322
    - Installation . . . 322
    - Equipment and Location . . . 322
    - Ultrasound Procedure . . . 322
- Interventional Procedure . . . 326
    - Infiltration/Test Block . . . 326
        - Indications . . . 326
        - Technique . . . 326
        - PNS . . . 326
        - RFP . . . 326
- Morphological Data: Sonoanatomy . . . 328
    - Installation . . . 328
        - Equipment and Location . . . 328
        - Ultrasound Procedure . . . 328
- Interventional Procedure . . . 332
    - Infiltration/Test Block . . . 332
        - Indication . . . 332
        - Technique . . . 332
    - PNS . . . 332
        - Indications . . . 332
        - Technique . . . 332
    - RFP . . . 332
        - Indication . . . 332
        - Technique . . . 332
- Surgical Procedure . . . 336
    - Surgical Indications . . . 336
        - At the Femoral Trigone . . . 336
    - Technical Pitfalls . . . 336

The Sciatic Nerve . . . 340
- Morphological Data . . . 340
    - Origin . . . 340
    - Path . . . 340
    - Neurovascular Relations . . . 346
    - Collateral Branches . . . 346
    - Terminal Branches . . . 346
    - Motor Function . . . 346

  Sensitive Function . . . 346
  Anastomoses . . . 346
Pathology . . . 356
  Aetiology . . . 356
  Clinical Significance . . . 356
  Clinical Forms . . . 356
  Explorations . . . 356
  Treatment . . . 356
Morphological Data: Sono Anatomy . . . 358
  Installation . . . 358
  Equipment and Location . . . 358
  Ultrasound Procedure . . . 358
  Piriformis Syndrome . . . 358
Interventional Procedure . . . 364
  Infiltration/Test Block . . . 364
    Indication . . . 364
    Technique . . . 364
  PNS . . . 364
    Technique . . . 364
Surgical Procedure . . . 366
  Surgical Indications . . . 366
  Surgical Approaches . . . 366
    On the Buttock . . . 366
    At the Thigh . . . 368
  Technical Pitfalls . . . 368

The Tibial Nerve . . . 372
Morphological Data . . . 372
  Origin . . . 372
  Path . . . 372
  Neurovascular Relations . . . 372
  Collateral Branches . . . 380
  Terminal Branches . . . 380
  Motor Function . . . 380
  Sensitive Function . . . 380
  Anastomoses . . . 380
Pathology . . . 386
  Soleus Syndrome . . . 386
  Aetiology . . . 386
  Clinical Significance . . . 386
  Explorations . . . 386
  Treatment . . . 386
  Tarsal Tunnel Syndrome . . . 388
  Aetiology . . . 388
  Clinical Significance . . . 388
  Clinical Forms . . . 388
  Explorations . . . 388
  Treatment . . . 388

Morphological Data: Sono Anatomy . . . 390
  Installation. . . . 390
  Equipment and Location . . . 390
  Ultrasound Procedure . . . 390
Interventional Procedure . . . 394
  Infiltration/Test Block . . . 394
    Infiltration at the Proximal Part of the Tibial Nerve . . . 394
  Technique . . . 394
    Indication . . . 396
  Technique . . . 396
    RFP . . . 396
    PNS . . . 396
    Sural Nerve . . . 398
  Installation. . . . 398
  Equipment and Location . . . 398
  Ultrasound Procedure . . . 398
  Infiltration/Test Block . . . 400
    Indications . . . 400
    Technique . . . 400
    RFP . . . 400
Surgical Procedure . . . 402
  Surgical Indications. . . . 402
    In the Leg . . . 402
    Skin Incision . . . 402
    Nervous Exposure. . . . 402
  Technical Pitfalls . . . 402
  Surgical Indications. . . . 404
    At the Ankle . . . 404
    Skin Incision . . . 404
    Nervous Exposure. . . . 404
  Technical Pitfalls . . . 404

The Fibular Nerve . . . 408
Morphological Data . . . 408
  Origin . . . 408
  Path . . . 408
  Neurovascular Relations . . . 408
  Collateral Branches . . . 408
  Terminal Branches . . . 414
  Motor Function . . . 414
  Sensitive Function . . . 414
  Anastomoses . . . 414
Pathology . . . 420
  Fibular Nerve Injury . . . 420
  Aetiology. . . . 420
  Clinical Significance . . . 420
  Clinical Forms . . . 420

- Explorations . . . 420
- Treatment . . . 420

Morphological Data: Sono Anatomy . . . 422
- Installation. . . . 422
- Equipment and Location . . . 422
- Ultrasound Procedure . . . 422
  - Identification of the Common Fibular Nerve in the Cervix . . . 422
- Deep Fibular Nerve . . . 424
  - Installation . . . 424
  - Equipment and Location. . . . 424
  - Ultrasound Procedure . . . 424
- Superficial Fibular Nerve . . . 424
  - Installation . . . 424
  - Equipment and Location. . . . 424
  - Ultrasound Procedure . . . 424

Interventional Procedure . . . 432
- Infiltration/Test Block at the Fibula Neck. . . . 432
  - Technique . . . 432
- Surgical PNS Implantation at the Fibula Neck . . . 432
  - Technique . . . 432
- Infiltration/Test Block at the Tarsal Tunnel. . . . 432
  - Indication . . . 432
  - Technique . . . 432
  - RFP . . . 432

Surgical Procedure . . . 434
- Surgical Indications. . . . 434
  - In the Leg . . . 434
- Technical Pitfalls. . . . 434
- PNS by Surgery at the Fibula Neck . . . 434

The Lateral Cutaneous Nerve . . . 438

Morphological Data . . . 438
- Origin . . . 438
- Path . . . 438
- Neurovascular Relations . . . 438
- Terminal Branches . . . 438
- Sensitive Function. . . . 442

Pathology . . . 444
- Meralgia Paraesthetica . . . 444
- Aetiology. . . . 444
- Clinical Significance . . . 444

Morphological Data: Sono Anatomy . . . 446
- Installation. . . . 446
- Equipment and Location . . . 446
- Ultrasound Procedure . . . 446

Interventional Procedure . . . 450

Infiltration/Test Block 450
    Indication 450
    Technique 450
PNS 450
    Indication 450
    Technique 450
RFP 450
    Technique 450
Surgical Procedure: Lateral Femoral Cutaneous Nerve Decompression 452
Surgical Description 452
    Skin Incision 452
    Nervous Exposure 452

The Other Nerves 456
The Iliohypogastric Nerve 456
    Morphological Data 456
    Origin 456
    Path 456
    Neurovascular Relations 456
    Collateral Branches 456
    Terminal Branches 456
    Sensitive Function 456
    Anastomoses 456
The Ilioinguinal Nerve 458
    Morphological Data 458
        Origin 458
        Path 458
        Neurovascular Relations 458
        Terminal Branches 458
        Sensitive Function 458
Pathology 460
    Entrapment Neuropathies of the Ilioinguinal Nerve and of the Hypogastric Nerve 460
    Aetiology 460
    Clinical Significance 460
    Clinical Forms 460
    Treatment 460
Bibliography 462

Index 464

List of Videos

Video. 4.1 Brachial plexus sonoanatomy. © Prismatics 2020. All rights reserved
Video. 5.1 Axillary nerve origin. © Prismatics 2020. All rights reserved
Video. 5.2 Axillary nerve path. © Prismatics 2020. All rights reserved
Video. 5.3 Axillary nerve neurovascular relations. © Prismatics 2020. All rights reserved
Video. 5.4 Axillary nerve collateral branches. © Prismatics 2020. All rights reserved
Video. 5.5 Axillary nerve terminal branches. © Prismatics 2020. All rights reserved
Video. 5.6 Axillary nerve motor function. © Prismatics 2020. All rights reserved
Video. 5.7 Axillary nerve sensitive function. © Prismatics 2020. All rights reserved
Video. 5.8 Axillary nerve sonoanatomy. © Prismatics 2020. All rights reserved
Video. 6.1 Musculocutaneous nerve origin. © Prismatics 2020. All rights reserved
Video. 6.2 Musculocutaneous nerve path. © Prismatics 2020. All rights reserved
Video. 6.3 Musculocutaneous nerve neurovascular relations. © Prismatics 2020. All rights reserved
Video. 6.4 Musculocutaneous nerve collateral branches. © Prismatics 2020. All rights reserved
Video. 6.5 Musculocutaneous nerve terminal branches. © Prismatics 2020. All rights reserved
Video. 6.6 Musculocutaneous nerve motor function. © Prismatics 2020. All rights reserved
Video. 6.7 Musculocutaneous nerve sensitive function. © Prismatics 2020. All rights reserved
Video. 6.8 Musculocutaneous nerve sonoanatomy arm. © Prismatics 2020. All rights reserved
Video. 7.1 Radial nerve origin. © Prismatics 2020. All rights reserved
Video. 7.2 Radial nerve path. © Prismatics 2020. All rights reserved
Video. 7.3 Radial nerve neurovascular relations. © Prismatics 2020. All rights reserved
Video. 7.4 Radial nerve collateral branches. © Prismatics 2020. All rights reserved
Video. 7.5 Radial nerve terminal branches. © Prismatics 2020. All rights reserved
Video. 7.6 Radial nerve motor function. © Prismatics 2020. All rights reserved
Video. 7.7 Radial nerve sensitive function. © Prismatics 2020. All rights reserved
Video. 7.8 Radial nerve sonoanatomy arm. © Prismatics 2020. All rights reserved
Video. 7.9 Radial nerve sonoanatomy forearm. © Prismatics 2020. All rights reserved
Video. 8.1 Median nerve origin. © Prismatics 2020. All rights reserved
Video. 8.2 Median nerve path. © Prismatics 2020. All rights reserved
Video. 8.3 Median nerve neurovascular relations. © Prismatics 2020. All rights reserved
Video. 8.4 Median nerve collateral branches. © Prismatics 2020. All rights reserved
Video. 8.5 Median nerve terminal branches. © Prismatics 2020. All rights reserved
Video. 8.6 Median nerve motor function. © Prismatics 2020. All rights reserved
Video. 8.7 Median nerve sensitive function. © Prismatics 2020. All rights reserved
Video. 8.8 Median nerve sonoanatomy arm. © Prismatics 2020. All rights reserved
Video. 8.9 Median nerve sonoanatomy forearm. © Prismatics 2020. All rights reserved
Video. 9.1 Ulnar nerve origin. © Prismatics 2020. All rights reserved
Video. 9.2 Ulnar nerve path. © Prismatics 2020. All rights reserved
Video. 9.3 Ulnar nerve neurovascular relations. © Prismatics 2020. All rights reserved
Video. 9.4 Ulnar nerve collateral branches. © Prismatics 2020. All rights reserved
Video. 9.5 Ulnar nerve terminal branches. © Prismatics 2020. All rights reserved
Video. 9.6 Ulnar nerve motor function. © Prismatics 2020. All rights reserved
Video. 9.7 Ulnar nerve sensitive function. © Prismatics 2020. All rights reserved
Video. 9.8 Ulnar nerve sonoanatomy arm. © Prismatics 2020. All rights reserved

Video. 9.9 Ulnar nerve sonoanatomy forearm. © Prismatics 2020. All rights reserved
Video. 10.1 Suprascapular nerve origin. © Prismatics 2020. All rights reserved
Video. 10.2 Suprascapular nerve path. © Prismatics 2020. All rights reserved
Video. 10.3 Suprascapular nerve neurovascular relations. © Prismatics 2020. All rights reserved
Video. 10.4 Suprascapular nerve collateral branches. © Prismatics 2020. All rights reserved
Video. 10.5 Suprascapular nerve terminal branches. © Prismatics 2020. All rights reserved
Video. 10.6 Suprascapular nerve motor function. © Prismatics 2020. All rights reserved
Video. 10.7 Suprascapular nerve sonoanatomy. © Prismatics 2020. All rights reserved
Video. 11.1 Long thoracic nerve origin. © Prismatics 2020. All rights reserved
Video. 11.2 Long thoracic nerve path. © Prismatics 2020. All rights reserved
Video. 11.3 Long thoracic nerve neurovascular relations. © Prismatics 2020. All rights reserved
Video. 11.4 Long thoracic nerve terminal branches. © Prismatics 2020. All rights reserved
Video. 11.5 Long thoracic nerve motor function. © Prismatics 2020. All rights reserved
Video. 13.1 Obturator nerve origin. © Prismatics 2020. All rights reserved
Video. 13.2 Obturator nerve path. © Prismatics 2020. All rights reserved
Video. 13.3 Obturator nerve neurovascular relations. © Prismatics 2020. All rights reserved
Video. 13.4 Obturator nerve collateral branches. © Prismatics 2020. All rights reserved
Video. 13.5 Obturator nerve terminal branches. © Prismatics 2020. All rights reserved
Video. 13.6 Obturator nerve motor function. © Prismatics 2020. All rights reserved
Video. 13.7 Obturator nerve sensitive function. © Prismatics 2020. All rights reserved
Video. 13.8 Obturator nerve sonoanatomy. © Prismatics 2020. All rights reserved
Video. 14.1 Femoral nerve origin. © Prismatics 2020. All rights reserved
Video. 14.2 Femoral nerve path. © Prismatics 2020. All rights reserved
Video. 14.3 Femoral nerve neurovascular relations. © Prismatics 2020. All rights reserved
Video. 14.4 Femoral nerve collateral branches. © Prismatics 2020. All rights reserved
Video. 14.5 Femoral nerve terminal branches. © Prismatics 2020. All rights reserved
Video. 14.6 Femoral nerve motor function. © Prismatics 2020. All rights reserved
Video. 14.7 Femoral nerve sensitive function. © Prismatics 2020. All rights reserved
Video. 14.8 Femoral nerve sonoanatomy. © Prismatics 2020. All rights reserved
Video. 15.1 Sciatic nerve origin. © Prismatics 2020. All rights reserved
Video. 15.2 Sciatic nerve path. © Prismatics 2020. All rights reserved
Video. 15.3 Sciatic nerve neurovascular relations. © Prismatics 2020. All rights reserved
Video. 15.4 Sciatic nerve collateral branches. © Prismatics 2020. All rights reserved
Video. 15.5 Sciatic nerve terminal branches. © Prismatics 2020. All rights reserved
Video. 15.6 Sciatic nerve motor function. © Prismatics 2020. All rights reserved
Video. 15.7 Sciatic nerve sensitive function. © Prismatics 2020. All rights reserved
Video. 15.8 Sciatic nerve sonoanatomy. © Prismatics 2020. All rights reserved
Video. 16.1 Tibial nerve origin. © Prismatics 2020. All rights reserved
Video. 16.2 Tibial nerve path. © Prismatics 2020. All rights reserved
Video. 16.3 Tibial nerve neurovascular relations. © Prismatics 2020. All rights reserved
Video. 16.4 Tibial nerve collateral branches. © Prismatics 2020. All rights reserved
Video. 16.5 Tibial nerve terminal branches. © Prismatics 2020. All rights reserved
Video. 16.6 Tibial nerve motor function. © Prismatics 2020. All rights reserved
Video. 16.7 Tibial nerve sensitive function. © Prismatics 2020. All rights reserved
Video. 16.8 Tibial nerve sonoanatomy. © Prismatics 2020. All rights reserved
Video. 17.1 Common fibular nerve origin. © Prismatics 2020. All rights reserved
Video. 17.2 Common fibular nerve path. © Prismatics 2020. All rights reserved

Video. 17.3 Common fibular nerve neurovascular relations. © Prismatics 2020. All rights reserved
Video. 17.4 Common fibular nerve collateral branches. © Prismatics 2020. All rights reserved
Video. 17.5 Common fibular nerve terminal branches. © Prismatics 2020. All rights reserved
Video. 17.6 Common fibular nerve motor function. © Prismatics 2020. All rights reserved
Video. 17.7 Common fibular nerve sensitive function. © Prismatics 2020. All rights reserved
Video. 17.8 Common fibular nerve sonoanatomy. © Prismatics 2020. All rights reserved
Video. 18.1 Lateral femoral cutaneous nerve origin. © Prismatics 2020. All rights reserved
Video. 18.2 Lateral femoral cutaneous nerve path. © Prismatics 2020. All rights reserved
Video. 18.3 Lateral femoral cutaneous nerve neurovascular relations. © Prismatics 2020. All rights reserved
Video. 18.4 Lateral femoral cutaneous nerve terminal branches. © Prismatics 2020. All rights reserved
Video. 18.5 Lateral femoral cutaneous nerve sensitive function. © Prismatics 2020. All rights reserved
Video. 19.1 Iliohypogastric ilioinguinal nerves origin. © Prismatics 2020. All rights reserved
Video. 19.2 Iliohypogastric ilioinguinal nerves path. © Prismatics 2020. All rights reserved
Video. 19.3 Iliohypogastric ilioinguinal nerves sensitive function. © Prismatics 2020. All rights reserved

Part I

MORPHOLOGICAL AND FUNCTIONAL ANATOMY OF THE PERIPHERAL NERVE

The Normal Nerve

Morpho-Functional Anatomy

General Organization of the Peripheral Nerve

Peripheral nerve is the “cable” used by the motor, sensory and vegetative neurons’ axons to circulate in the peripheral nervous system. It conveys information between these neurons and their effectors in both directions (sensitive receptors, skeletal muscles and viscera). The afferents towards the periphery correspond to the motor and autonomous functions of the nerve whilst the efferents, originating from the periphery and in charge of carrying information towards the central nervous system, correspond to the sensory nucleus of the nerve. The information is transmitted as nerve impulses, the properties of which depend on, amongst other things, the intrinsic characteristics of the nerve itself.

In adult state, the nerve fibres, constituted of axons and Schwann cells that are associated with them, are grouped in fascicles, wrapped in the perineurium. The perineurium is constituted of layers of perineurial cells of fibroblastic origin, separated by bundles of collagen and linked together by tight junctions. The nerve fibres are associated with Schwann cells which are the only glial cells of the peripheral nervous system. These have an essential role in axon maintenance, myelination and regeneration processes. The nerve fascicles are contained in an areolar connective tissue known as epineurium which contains fibroblasts, collagen and fat in variable proportions. This sheath participates in the fixation of the nerve inside the surrounding structures. It contains the lymphatic and vascular network (vasa nervorum) which crosses the perineurium to communicate with the network of arterioles and venules in the endoneurium. The epineurium constitutes between 30 and 70% of the total surface of the section of a nerve trunk (Figure 1).

A nerve can be constituted of between one and a hundred or so fascicles, their number and distribution being constantly variable thanks to a great number of exchanges of anastomoses.

In addition, to a macroscopic level, anastomoses between different nerves are frequent, for instance, the Martin-Gruber anastomosis between the ulnar and median nerve (Figure 2).

It possesses a resistance to stretching thanks to the double action of the “undulating” architecture of the fascicles and the nerve fibres that it contains (Figure 3), but also thanks to the elasticity of the perineurium. The homeostasis of this micro-environment is obtained and maintained by a complex vascular system and by the active barrier constituted by the perineurium. Like the central nervous system, a real blood–nerve barrier is found, its tightness being linked to the properties of the perineurium and to the presence of tight junctions (zonula occludens) between the capillary endothelial cells that penetrate into the endoneurium and the perineurium cells.

❶ Nerve fascicle

❷ Vasa nervorum : arteriole

❸ Vasa nervorum : venule

❹ Epineurium

❺ Perineurium

❻ Nerve fibre

❼ Capillary

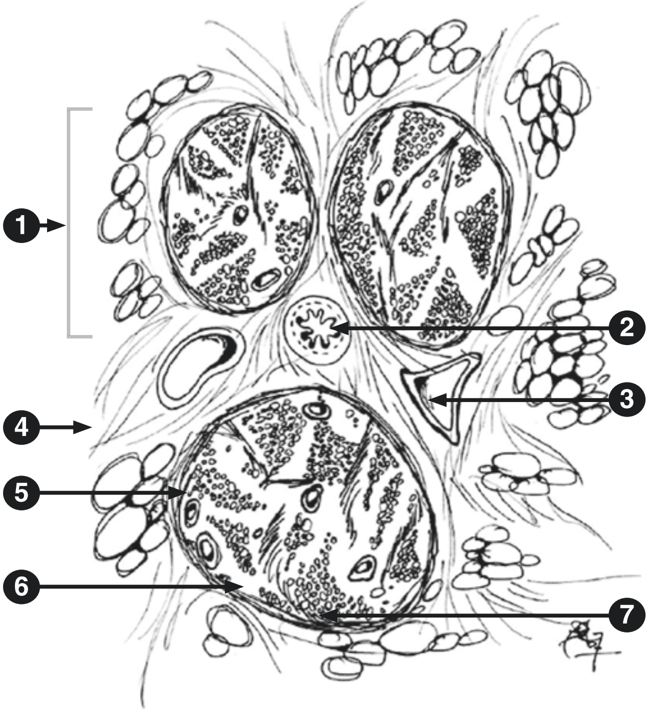

Figure 1. Axial section of a peripheral nerve.

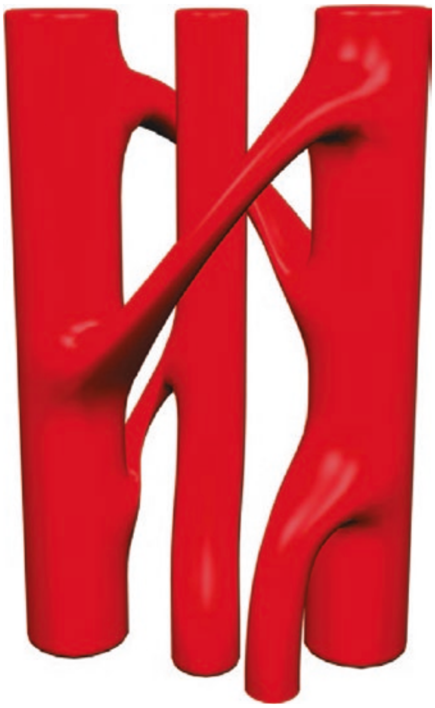

Figure 2. Anastomoses of various nerves.

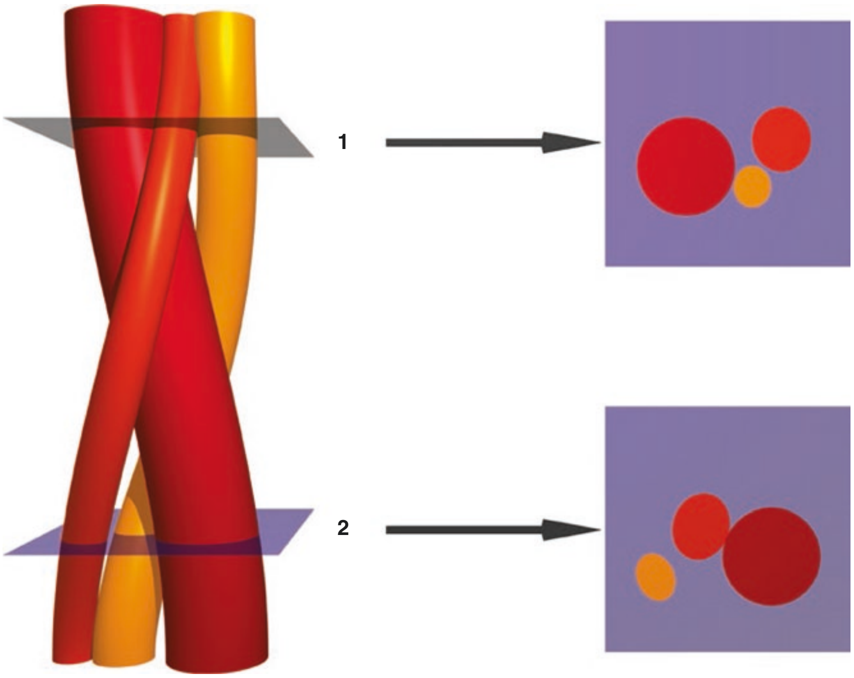

Figure 3. Architecture of fascicles and nerve fibres.

The Normal Nerve

The Structure and Physiology of the Nerves

Axon

The axon is the cylindrical prolongation of the cytoplasm of the neuron. Its main role is the transmission of nerve impulses. It can only be conceived in the context of a functional unity between the neuron and its target. Its survival is linked to that of the neurons and its targets. Since it does not possess its own capacity of protein biosynthesis, its contents are carried from the core to the periphery by the axonal flow.

Cytoskeleton

The axonal cytoskeleton has a microfibrillar structure composed of three main groups of proteins: the microfilaments, the microtubules and the intermediate filaments including the neurofilaments. These contribute to the maintaining of the shape and growth of the axon. The neurofilaments are constituted of an assembly of three proteins which spread apart during the process of phosphorylation, giving them a fundamental role in the determination of the axonal diameter.

This diameter is correlated with myelination, and it is therefore an essential structural parameter. The microfilaments, constituted of an assembly of polymers of globular actin (G-actin), are generally located in areas in motion and at the level of the membrane anchorages which have a significant role in the mobility of the axonal growth cone and in the synaptogenesis. The microtubules, which are heterodimers of alpha- and beta-tubulin, form hollow tubules on which many other proteins implicated in the processes of assembly and stabilization as well as the interactions with the rest of the cytoskeleton get fixed on. These microtubules participate in the growth and in the axonal flow.

Axonal Flow

The axonal flow constantly circulates in both anterograde and retrograde directions at variable speeds according to the elements transported and the type of fibres (Table 1). It guarantees a permanent communication between neurons, axon terminations and target cells. It is divided into two fast anterograde and retrograde transports, one slow anterograde transport and one path reserved for mitochondria. On the one hand, the fast anterograde flow transports the vesicular and tubular structures containing the precursors of the neurotransmitters and the membrane proteins, and on the other hand, it transports the mitochondria and membrane lipids. The slow anterograde flow carries the structural proteins of the cytoskeleton and polyproteins. The fast retrograde flow takes back the cellular waste, transports enzymes, growth factors and lysosomal vesicles and participates in the retrocontrol of the activity of the soma by the target. This transport is allowed by microtubules thanks to motor proteins (Figure 4): principally, kinesin (for the anterograde flow) and dynein (for the retrograde flow).

For the peripheral motor neurons, it is the neuromuscular synapse that corresponds to the extremity of the axon termination relating to its target. At this level, the electric signal is transformed in a chemical signal by mechanisms described hereafter.

The arrival of the impulse causes the entrance of calcium by the opening of the voltage-dependent calcium channels, thus triggering a spate of intracellular activation ending with the fusion of the membrane and the synaptic vesicles containing the neurotransmitters, liberated in the synaptic cleft by exocytosis.

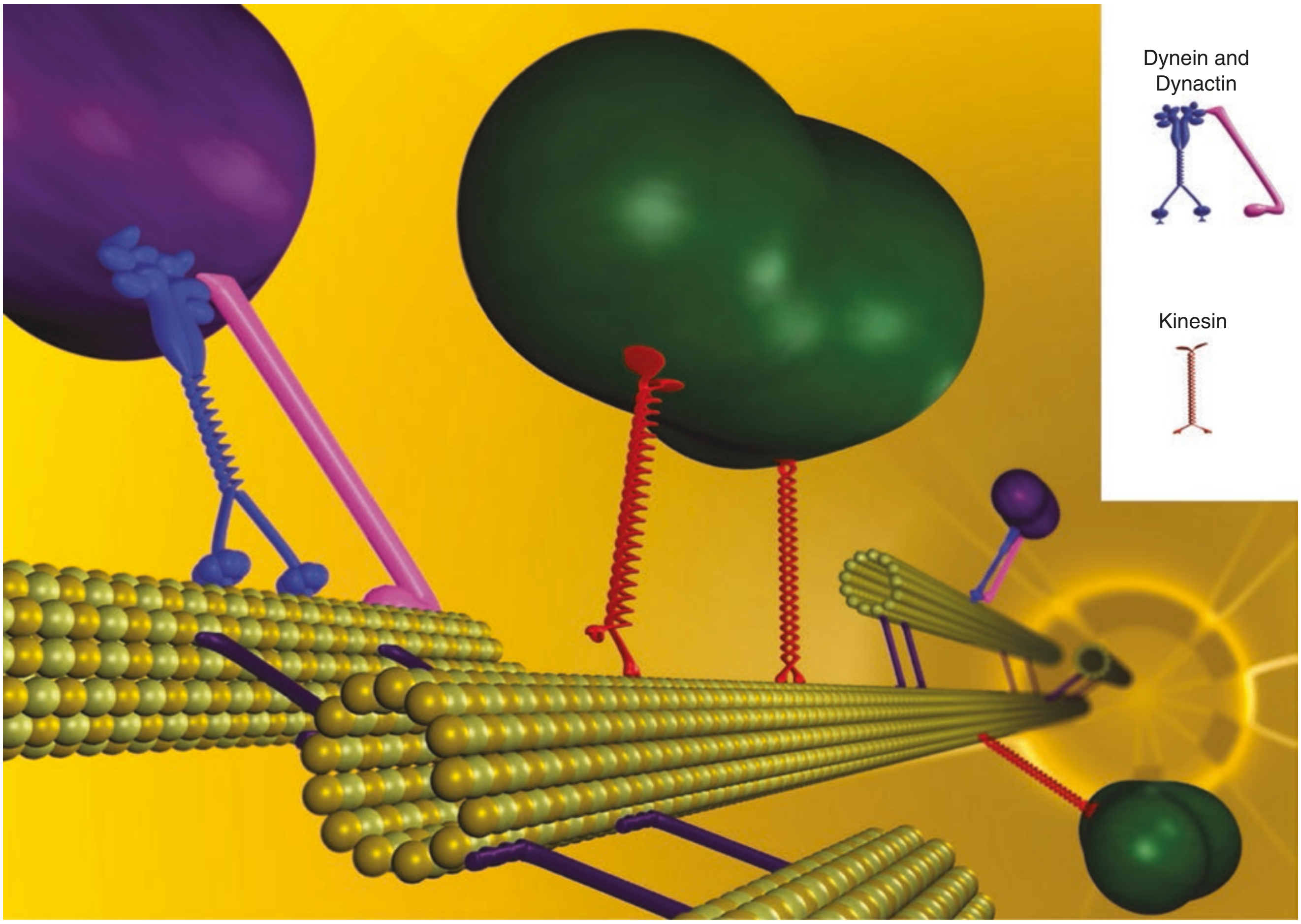

Figure 4. Axonal cytoskeleton.

Fibre type		Role	Myelination	Diameter (µm)	Conduction speed (m/s)
Sensory					
Aαβ	Ia	Proprioception: muscle spindles	+	12–20	70–120
	Ib	Golgi tendon organ	+		
	II	Cutaneous sensitivity: touch	+	5–12	30–70
Aδ	III	Cutaneous pressure: temperature	+	2–5	12–30
C	IV	Cutaneous pain: pain	–	0.4–1.2	0.5–2

Table 1. Classification of nerve fibres.

Schwann Cell and Myelination

The Schwann cells are the only glial cells represented in the peripheral nervous system (Figure 5). In the mature peripheral nerve, Schwann cells are distributed as longitudinal chains running along the axons. There is a direct relationship between the thickness of the myelin sheath and the diameter of the axon and between the diameter of the axon and the internodal distance. The increase of the myelin sheath's thickness and the internodal distance is correlated with that of the diameter of the axon (Figure 6).

Myelination (Figure 7) is observed in the peripheral nervous system (PNS) for axons with a diameter above 1–1.5 μm. The axon's diameter is not the only determining factor of myelination. It follows the histogenesis and happens later, after about 4 months of foetal life. The Schwann cell begins its myelination on a definite segment of the axon. The transitional area separating two myelinated segments is called node of Ranvier. The space separating two nodes of Ranvier is called the internodal space. The myelin sheath ends on each side of a node with a paranodal region.

Myelination speeds up nerve conduction. The conduction of the impulse is continuous (uninterrupted) in the unmyelinated fibres; the maximum speed obtained is limited to 15 m/s. In the myelinated fibres, the excitable membrane is confined to the nodes of Ranvier because the myelin possesses isolating properties. This conduction thus becomes saltatory, from node to node, and can attain speeds up to ten times its original (120 m/s). The number of impulses that can be carried by these fibres is also much greater. Myelination optimises the energetic output of the fibre.

The basal membrane of the Schwann cell directs the axon's growth.

①	Schwann cell
②	Schwann cell nucleus
③	Axon

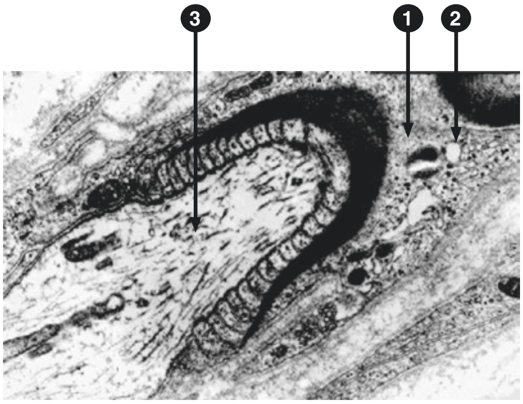

Figure 5. Schwann cell (electron microscopy).

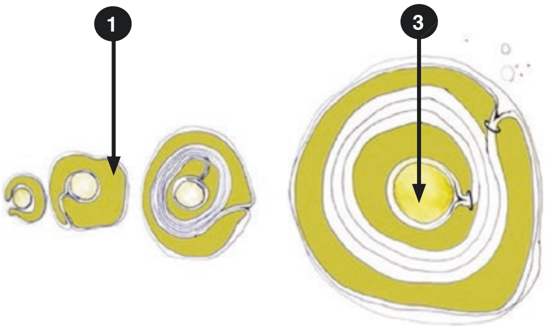

Figure 6. Myelination process (axial section).

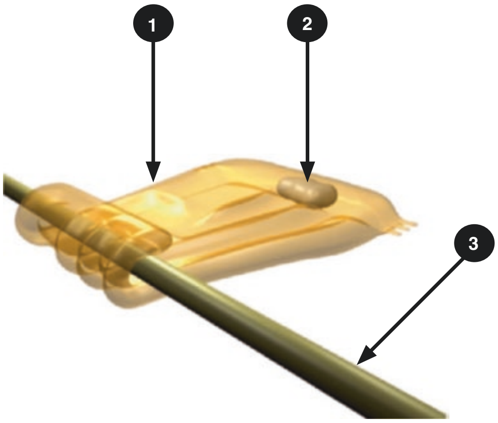

Figure 7. Myelination process.

Mechanical Properties of the Nerves

A peripheral nerve possesses a certain resistance to stretching, thanks to not only the double action of the "undulating" architecture of the fascicles (Figure 3) and the nerve fibres that it contains but also the elasticity of the perineurium. The tension forces first apply on the fascicle and then on the fibres which, due to this elasticity, keep their normal form for a long time. These forces provoke a shrinking of the fascicle's diameter and an increase of the pressure inside the fascicle that ends up compromising the vascularization of the nerve if they are applied for too long. A number of factors including the intensity, speed and duration of application of these constraints condition the resistance to stretching. The resistance to these compressing forces varies with the number of fascicles and the girth of the epineurium. The nerves which contain a great number of fascicles and a thin epineurium are weaker against compressing forces (type B fibres compared to type A, in Figure 8), as well as the roots that do not possess a structure corresponding to an epineurium and which have a thinner perineurium.

④ Nerve fascicle

⑤ Epineurium

⑥ Perineurium

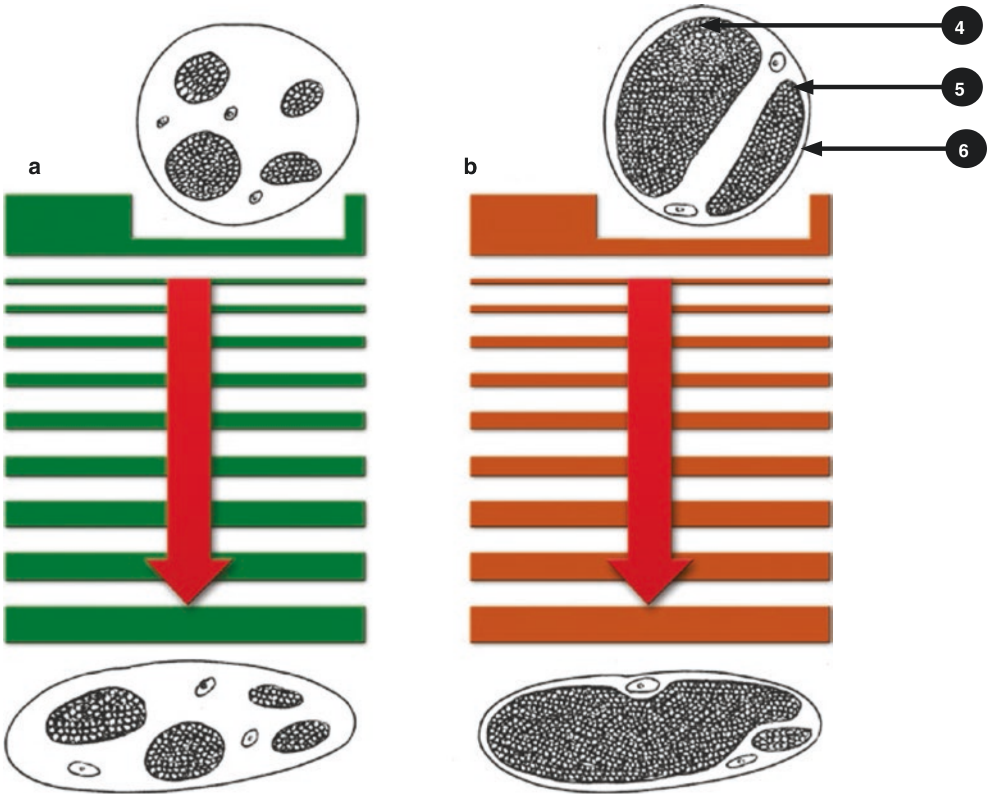

Figure 8. Strength model of a nerve against compression.

Vascularization of the Peripheral Nerves

This vascularization is special on many fronts. The axon's trophicity is particularly dependent of the endoneurial micro-environment because of the soma's remoteness. The homeostasis of this micro-environment is obtained and maintained by a complex vascular system and by the active barrier constituted by the perineurium. The arterial supply comes from the trunci which are closest to the nerve. Each artery is divided into a descending branch and an ascending branch before splitting into several epineurial branches. There are two distinct systems which are functionally independent but contain a great number of anastomoses: one is extrinsic and constituted of regional feeder vessels and arterio-capillary vessels of the epineurium, and the other is intrinsic and constituted of endoneurial capillaries in a longitudinal distribution (Figure 9). As a result, there is a considerable overlapping between the vascularised areas by the segmental arteries which cross them. The relatively low metabolic needs of the nerve compared to the high basal blood flow and the possibility to function in a situation of anaerobiosis grant the nerve a special resistance to ischemia. However, the central fascicular area remains weaker than the subperineurial area, probably because of a higher density of capillaries and a better penetration of the nutritive substances through the perineurium. There also seems to be a border zone of susceptibility to ischaemia between two longitudinal territories. As in the central nervous system, there is a real blood–nerve barrier, its tightness being linked to the properties of the perineurium and to the presence of tight junctions between the endothelial cells of the capillaries penetrating into the endoneurium and the perineurium cells. The epineural and transepineural vasa nervorum are innervated by thin plexuses made of amyelinic vegetative nerve fibres, some being sympathetic (vasoconstricting) and others being parasympathetic (vasodilating). The endoneural capillaries have a smooth, underdeveloped muscular system that suggests a weak autoregulation.

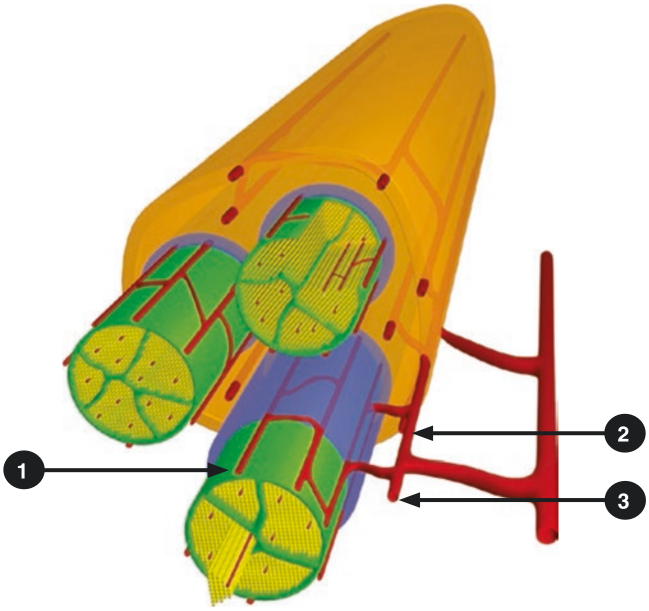

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Figure 9a. Longitudinal view of vascularization.

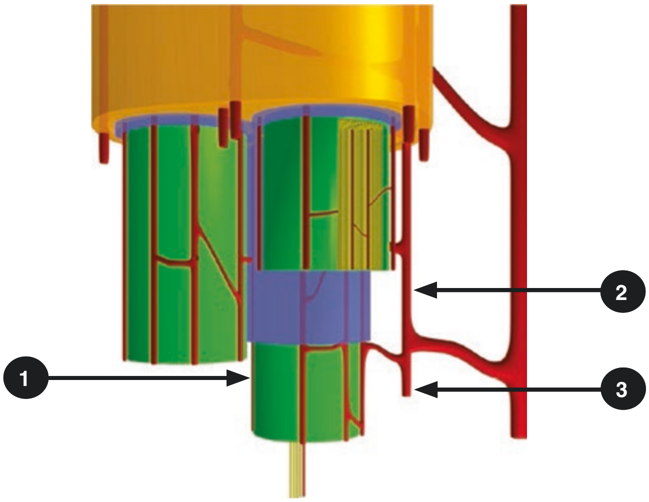

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Figure 9b. Side view of vascularization.

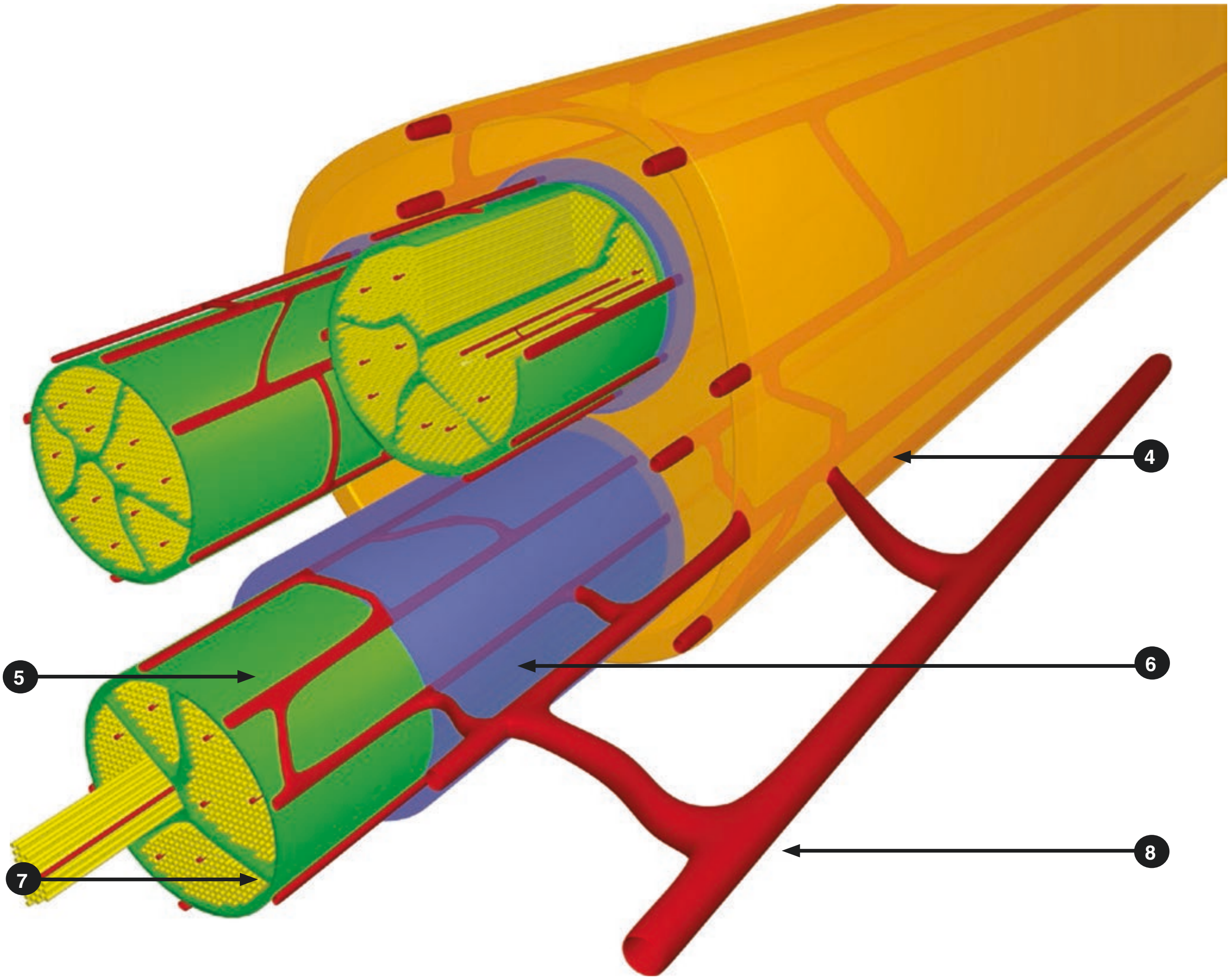

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Figure 9c. Microstructure of a peripheral nerve.

① Epineural arterial branch
② Ascending arterial branch
③ Descending arterial branch
④ Epineurium and connective tissue
⑤ Endoneurium
⑥ Perineurium
⑦ Axon
⑧ Vasa nervorum

Neuromuscular Junction and Transmission

The musculoskeletal system is the mechanical interface between our nervous system and the external world. The mechanical properties of muscles have been very largely preserved during the phylogenesis of the vertebrates. These have been crucial in the adaptation of the neuronal mechanisms for movement.

A single motor neuron is bombarded by synaptic stimuli, which will result in determining the manner of and intensity at which the target muscle fibre will participate in the realization of a motor programme. This response of the nerve cell to a stimulus is allowed by a modification of its membrane properties. The neuromuscular synapse is the junction area between the axon of a motor neuron and a muscular cell. In mammalians (with a few exceptions), there is no real contact at the synaptic level. The synaptic gap (between 10 and 40 nm) separating these cells acts as an isolating structure.

This neuromuscular junction (NMJ) (Figure 10) is made up of the apposition of highly differentiated domains of three kinds of cells: the nerve termination of the motor neuron, the Schwann cell called "terminal" and the postsynaptic membrane of the muscle fibre. These three elements are surrounded or linked together by a basal lamina, which is a favourable micro-environment for the exchange of molecular signals that control the formation, maturation and sustenance of the NMJ. The NMJ forms a functionally and structurally differentiated complex, the goal of which is to guarantee the synaptic transmission within the neuromuscular apparatus by managing the propagation of the motor neuron's impulse towards the skeletal muscle fibre.

The nerve termination releases a neurotransmitter in the synaptic gap, the acetylcholine (ACh) , which connects on specific nicotinic receptors (the receptors of the acetylcholine or AChR), located under the invaginations' cristae or subneural folds of the postsynaptic membrane of the muscle fibre. The activation of these receptors causes a depolarization of the muscle membrane leading to a chain reaction named excitation–contraction coupling (ECC) inducing the contraction of the adjacent muscle fibre. Several tools have been developed to characterise in a simple way the morphological aspect of the normal NMJ and the abnormalities that ensue from the pathological modifications of these junctions. The advent of molecular biology has allowed the discovery of a great number of synaptic molecules concentrated at the junction and thus favoured the understanding of the physiopathological mechanisms implied in the phenomena of denervation and reinnervation and in neuromuscular pathologies. For example, the congenital myasthenic syndromes, which form a heterogeneous group of affections of genetic origin, lead to a dysfunction of the neuromuscular transmission. Their characterization relies on bringing to light structural abnormalities in the NMJ, mutations in the genes coding the concentrated proteins at the level of the motor areas, and on the molecular mechanisms by which such mutations induce the illness.

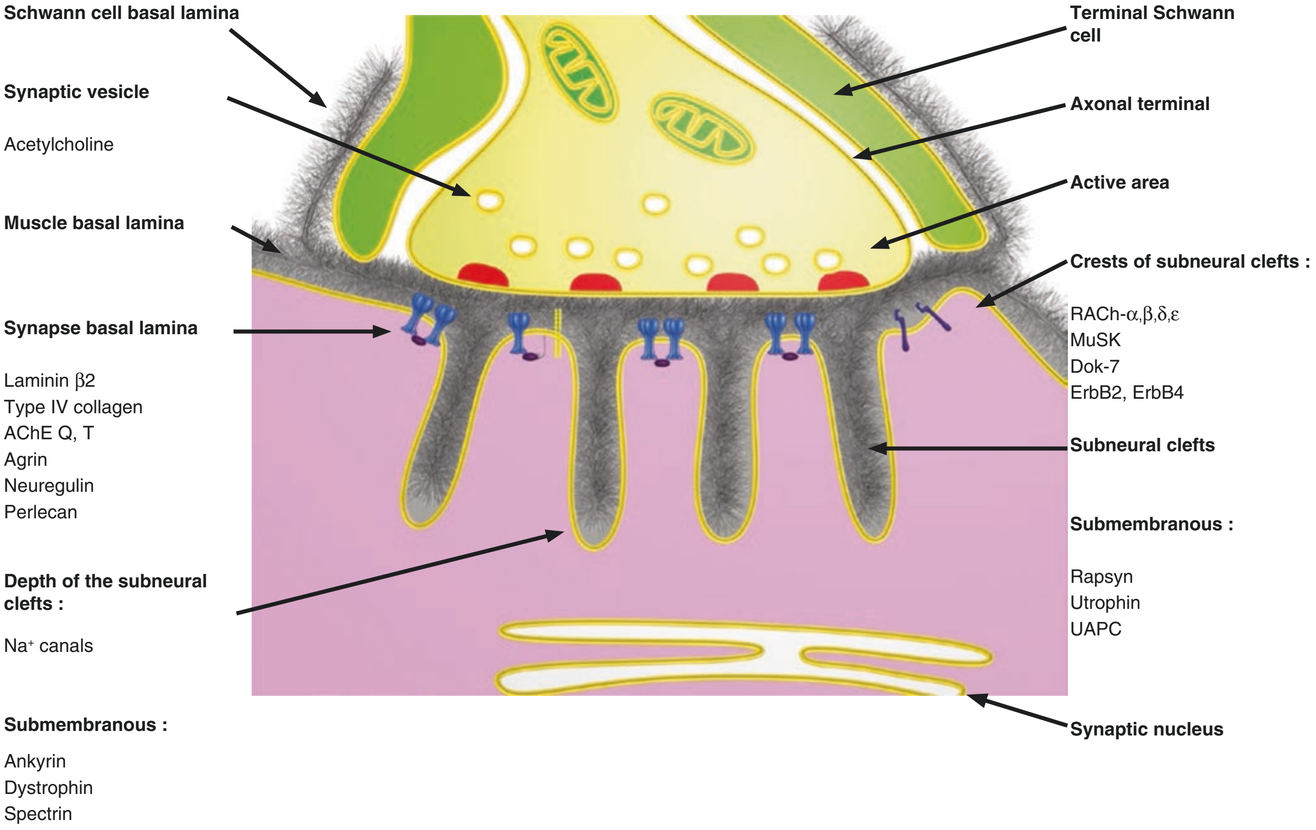
Schwann cell basal lamina
Synaptic vesicle
Acetylcholine
Muscle basal lamina
Synapse basal lamina
Laminin β2
Type IV collagen
AChE Q, T
Agrin
Neuregulin
Perlecan
Depth of the subneural clefts :
Na+ canals
Submembranous :
Ankyrin
Dystrophin
Spectrin
Terminal Schwann cell
Axonal terminal
Active area
Crests of subneural clefts :
RACh-α,β,δ,ε
MuSK
Dok-7
ErbB2, ErbB4
Subneural clefts
Submembranous :
Rapsyn
Utrophin
UAPC
Synaptic nucleus

Figure 10. The neuromuscular junction (According to Sanes and Lichtman 1999).

Main Mechanisms of Synaptic Formation

Synaptic formation is a necessary process during neuronal development allowing communication between two neurons. One of the main characteristics of the development of the nervous system is the specificity of its connections. As such, the axons' migration towards their target and the formation of the synapses are selective processes, implicating many recognition molecules, most of which remain unknown.

The synthesis and distribution of the acetylcholine receptors at the level of the postsynaptic membrane of the NMJ indeed seem regulated by anterograde signals originating from the motor neuron. The differentiation of axonal termination is however regulated by retrograde signals. The nerve and muscle have distinct roles in the differentiation of the synaptic compartment. The initial steps of this differentiation and formation of the neuromuscular junction require several postsynaptic molecular agents including receptor tyrosine kinase protein MuSK and rapsyn. The dependency on agrin or motor neuron remains controversial whilst the following steps of the axonal growth and the sustainment of the postsynaptic apparatus mostly depend on neural agrin and on a specific signal emanating from the nerve fibre, responsible for the dispersion of the remnants of aggregates of ectopic acetylcholine receptors, all this possibly managed by the acetylcholine itself. The neuregulin essentially intervenes in the sustainment of the Schwann cell which guides axonal growth. The synaptic formation of the central nervous system actually presents a high number of similarities with the development of motor innervations. This allows the study of some mechanisms of recovery of the nerve connections after a traumatic or degenerative nerve injury and thus leads to the discovery of new treatments that could favour recovery on a functional point of view.

One can distinguish three fundamental steps in synaptic formation: the creation of a connection between the growing axon and its target cell, the differentiation of the axonal growth cones into a nerve termination and finally the formation of postsynaptic structures in target cells. These steps depend on intercellular interactions mediated by signals, responsible for the recognition by the axon of the appropriate postsynaptic cell, and the coordination of the formation of various pre- and postsynaptic structures at the synapse's level.

As soon as there is contact between the extremity of a growing axon and a myotube, a neurotransmission occurs, even in a rudimentary form, notably by the intermediary of the acetylcholine vesicles. This leads to the creation of the synaptic zone, especially thanks to many retrograde signals, coming from the muscle and going towards the axon. Indeed, the intrinsic properties of the various involved cellular elements are not sufficient. Studies have shown that after a denervation synapses are able to regenerate, especially if there is a preserved postsynaptic membrane. Furthermore, the presynaptic specialization of the axon starts only after contact with a muscle. It is then obvious that a muscle feedback on the axons exists, but the actual mechanisms are yet to be known. Two types of cell adhesion molecules, the N-CAM and the N-cadherin, situated at the level of the axonal terminations and myotubes, would stabilise the contact between the muscle and nerve.

The synaptic formation completes that of the nervous system by giving it its functionality. It needs a rigorous spatio-temporal organization: the nerve termination has to reach a specific area of the target cell, and the synaptic membrane needs to be very sensible to the neurotransmitters sent by the corresponding nerve termination. This functional set has to be stable enough to subsist for a whole lifetime, but at the same time adaptable enough to evolve with the learning processes.

Synaptogenesis is a highly specific process as well: even though the pre- and postsynaptic cells are able to synthesise their own components, the exchange of many signals is necessary in order to coordinate their activity at all times. As for the NMJ, in vitro models have initially proved that two molecules, the agrin and the ARIA neuregulin β1, could be responsible for the accumulation, synthesis and maturation of the acetylcholine receptors. Knockout of the genes coding for these two molecules has been used in mice to clarify their role during the junction's development.

The latest concepts have allowed a very clear specification of the role of each of these molecules in the maturation of the NMJ. MuSK remains the hub of postsynaptic differentiation. The accumulation and synthesis of AChR are guided by agrin (aggregation of receptors by way of the interaction of the MuSK/agrin complex with the rapsyn but also with a characteristic action preventing their separation) and Dok-7 that allows their phosphorylation to MuSK. The maturation of AChR could also result from the interaction between agrin and MuSK via the implication of GTPases (Rac/Cdc42) in the transcriptional regulation of the receptors' subunits (Figure 11). The neuregulin emanating from the nerve would essentially act by its interaction with its receptors situated on the surface of the terminal Schwann cell and is now considered a key molecule in the sustainment of the Schwann cell and so, through these means, of nerve regeneration.

The involvement in the synapses of the CNS of some of these molecular actors illustrates quite well the complexity of the anterograde and retrograde interactions required for the formation, development and sustainment of the NMJ. The scientific interest aroused by the major challenge of public health to try and figure out the mechanisms allowing for neuron plasticity and reparation, especially at the level of the CNS, has led to the discovery of some factors influencing axon regeneration and opened the way to new therapeutic propositions, their aim being to restore function in the event of a nerve injury.

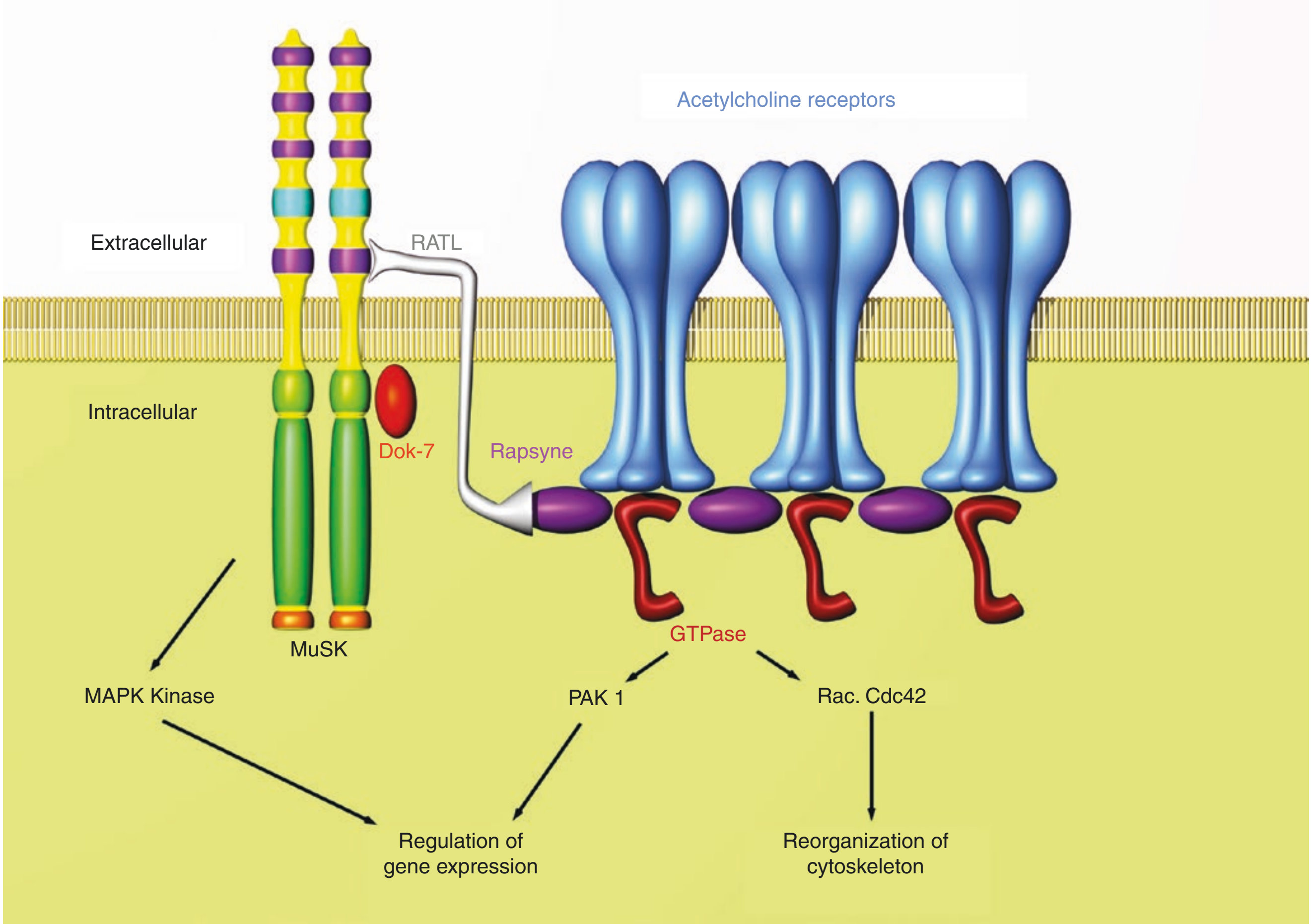
Acetylcholine receptors
Extracellular
RATL
Intracellular
Dok-7
Rapsyne
MuSK
GTPase
MAPK Kinase
PAK 1
Rac. Cdc42
Regulation of gene expression
Reorganization of cytoskeleton

Figure 11. Role of the kinase proteins in the transmission of nerve impulse (According to Valenzuele 1995; Zhou 1999).

The Injured Nerve

Physiology of the Damaged Nerve

Peripheral nerve injuries are frequent and can cause serious disabilities. Their treatment sometimes leads to functional regeneration which often remains incomplete and random, despite the practice of rather sophisticated surgical techniques.

Two main classifications of peripheral nerve injuries have been established by Seddon and Sunderland (Figure 1). Seddon suggests a segmentation of injuries based on the residual function within the nerve. This classification distinguishes three degrees: neurapraxia, axonotmesis and neurotmesis. Sunderland adds two more degrees between axonotmesis and neurotmesis.

Pathophysiological Mechanisms

The most common causes of nerve injuries are traffic accidents, mostly those involving motorcycles. Statistically, peripheral nerve injuries are more frequent in the upper limbs (73.5% of traumatic injuries), particularly involving the ulnar nerve. The injury mechanisms most frequently implicated are traction, division, crushing and in a moderate way ischaemia related with a compression on the peripheral nerve.

It seems important to insist on this type of damage in the sense that it is the one which characterizes the genesis of entrapment neuropathy, regardless of which nerve is afflicted by compression.

A brief compression will stop nerve conduction and axonal transport, leading to a total motor and sensory paralysis (acute ischaemia, followed by a regeneration occurring a few minutes later, e.g. the fibular nerve after keeping the legs crossed, numbness when waking up because of a compression of the median nerve at the brachial canal).

A chronic compression initially leads to a degeneration limited by the integrity of basal membranes. At the beginning, a distortion and an overlapping of the paranodal myelin emerge. Several layers of myelin can be involved, with a conduction slowdown. At the level of the affected segment, the myelin can retract itself in onion bulb formations and lead to a significant increase of endoneurial collagen. Ischaemic phenomena coexist with a breakdown of the blood–nerve barrier (Figure 2). Prolonged compression leads to a degeneration of the distal nerve, with disuse atrophy, the paralysis happening in a belated way. The relieving of the compression will lead to a complete regeneration of the function if it happens before the denervation. The compression syndrome treatment efficiency illustrates this. The previous myelin is replaced, and a proliferation of Schwann cells guarantees its reconstitution. Repeated cycles of demyelination and remyelination can follow and go so far as to coexist in neighbouring areas. The afflicted nerve segments show Schwann cells in an onion bulb shape and an increase in the density of the endoneurial interstitial tissue by proliferation of the collagen. The continuity of basal membranes allows for functional regeneration for a long time after treatment.

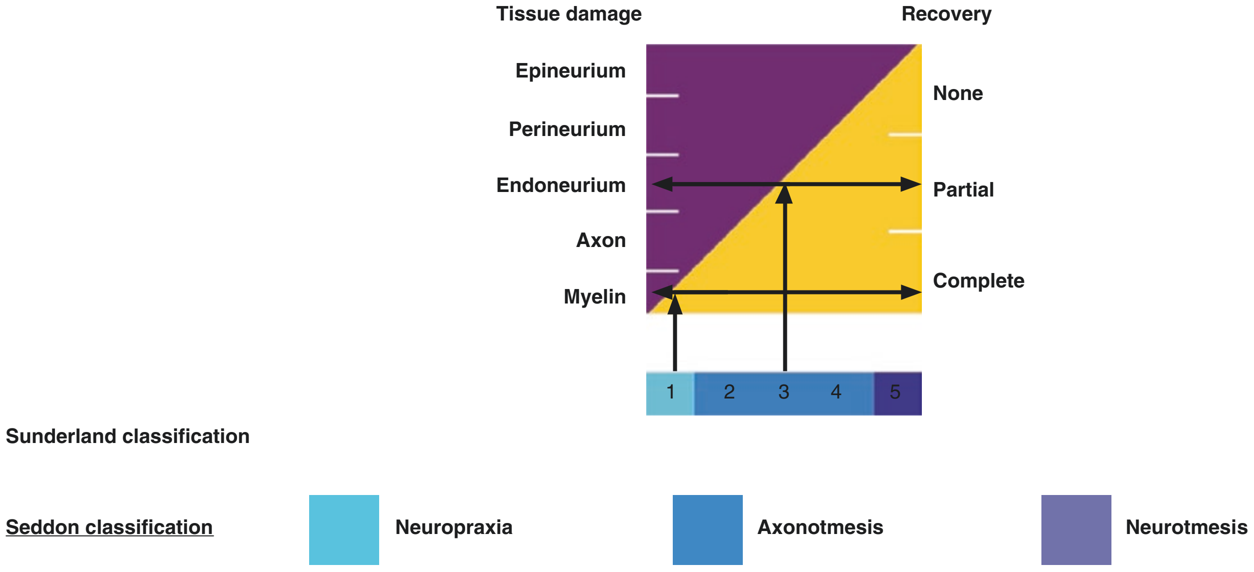
Tissue damage
Recovery
Epineurium
Perineurium
Endoneurium
Axon
Myelin
None
Partial
Complete
1
2
3
4
5
Sunderland classification
Seddon classification
Neuropraxia
Axonotmesis
Neurotmesis

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Figure 1. Diagram of recovery according to the level of tissue injury (According to Seddon (1943) and Sunderland (1951)).

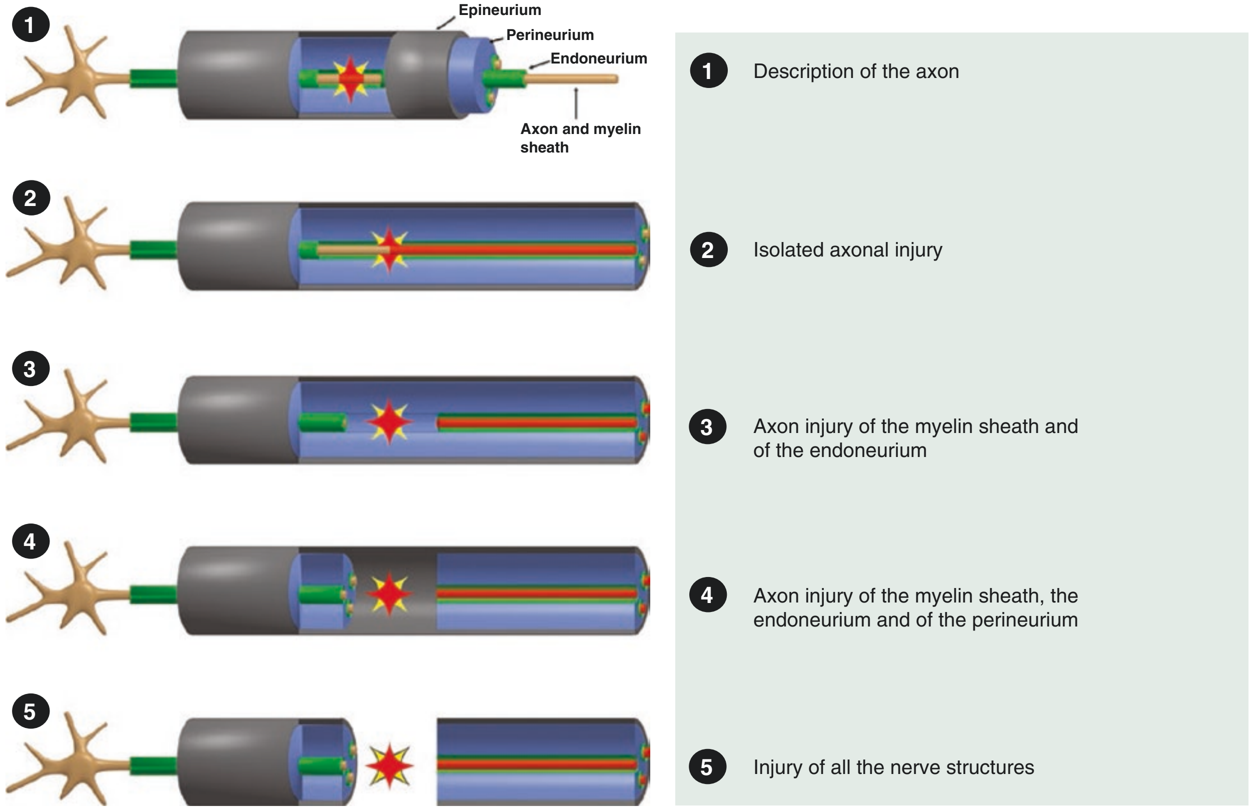
Epineurium
Perineurium
Endoneurium
Axon and myelin sheath
1 Description of the axon
2 Isolated axonal injury
3 Axon injury of the myelin sheath and of the endoneurium
4 Axon injury of the myelin sheath, the endoneurium and of the perineurium
5 Injury of all the nerve structures

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Figure 2. Various types of axon injury structure.

Nerve Degeneration

In cases of acute nerve damage or chronic compressions without division of the axonal continuity (injuries of the first degree), we find some modifications of the myelin sheath starting with a contusion extending up to the concerned paranodal area (Figure 3). It can extend over a few adjacent segments and cause a decrease in conduction speed. In acute cases, one can observe conduction blocks even though an electrophysiological test of each of the nerve's extremities remains normal. There is a regenerative process that leads to a remyelination after an elimination of the damaged myelin. In chronic compressions, successive demyelination–remyelination cycles lead to the formation of a segmental onion bulb-shaped morphology linked to the proliferation of Schwann cells and to the expansion of the interstitial endoneurial content invaded by collagenic material. In second-degree and above injuries, there are visible changes at the level of the injury's area, but it is mostly the distal segment that will suffer a process of anterograde degradation called Wallerian degeneration, according to a chain of events whose initial trigger is calcium dependent. The first modifications lead to a myelinic and axonal fragmentation and start in the first hours after the trauma. It takes place with the same kinetics as the Wallerian anterograde degeneration, namely a retrograde degeneration. It generally only affects some segments with an identical lesional sequence (Figure 4).

The degeneration reaches its peak after a division of the nerve containing in and of itself an interruption of the basal membranes and a functional failure of the emitting function of the neuron, the somatodendritic ramifications being the receiving function. The peripheral nerve's is unique, which differentiates it from the constituting elements of the central nervous system. The existence of initiated compensating mechanisms within the motor neurons during pathological or traumatic processes is accepted without doubt nowadays. It has thus been demonstrated that after axonal injuries, the peripheral nervous system's neurons are able to regenerate their axons to reinnervate various targets.

A : Diagram of a nerve under physiological conditions

B : Diagram of a possible traumatic injury

① Healthy neuron

② Myelin sheath

③ Axon

④ Cell nucleus

⑤ Injured myelin before phagocytosis

⑥ Injured myelin

⑦ Wallerian degeneration of the axonal swelling

⑧ Soma

⑨ Macrophage

A : About 24 hours after injury. Wallerian degeneration of the distal part of the peripheral nerve. First signs of chromatolysis.

B : 10 to 21 days after injury. First signs of denervation atrophy of the target muscle fibres. Band of Bungner along the proliferating Schwann cells. Formation of axonal growth cone at the level of the proximal swelling. Visible chromatolysis.

C : Several months after injury. Extensions of axonal sprouting growing at various speeds, among which one or several extend within the band of Bungner, but haven't reached their target. Advanced stage of muscle denervation. Regression of the chromatolysis reactions in the soma.

D : Reinnervation of the target organ by the faster-growing axons. The motor end plate becomes functional again and conduction is restored. Regression of the other extensions. Progressive remyelination. The muscle fibres recover a subnormal thickness.

E : Formation of a neuroma. The muscle fibres that were denervated for more than a year destructure and are subject to an important interstitial fibrosis.

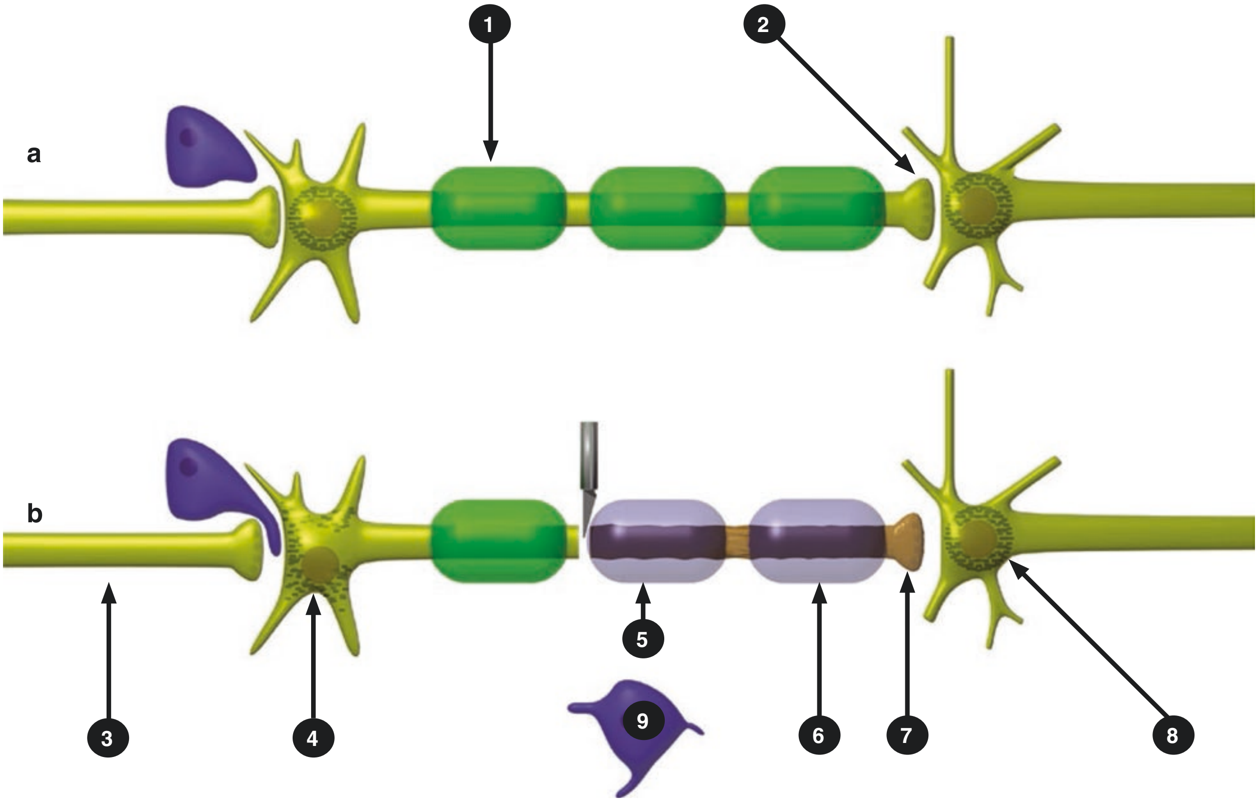
1
2
a
b
5
9
3
4
6
7
8

Figure 3. Traumatic injury of an axon (According to Keirstead et al. (1999)).

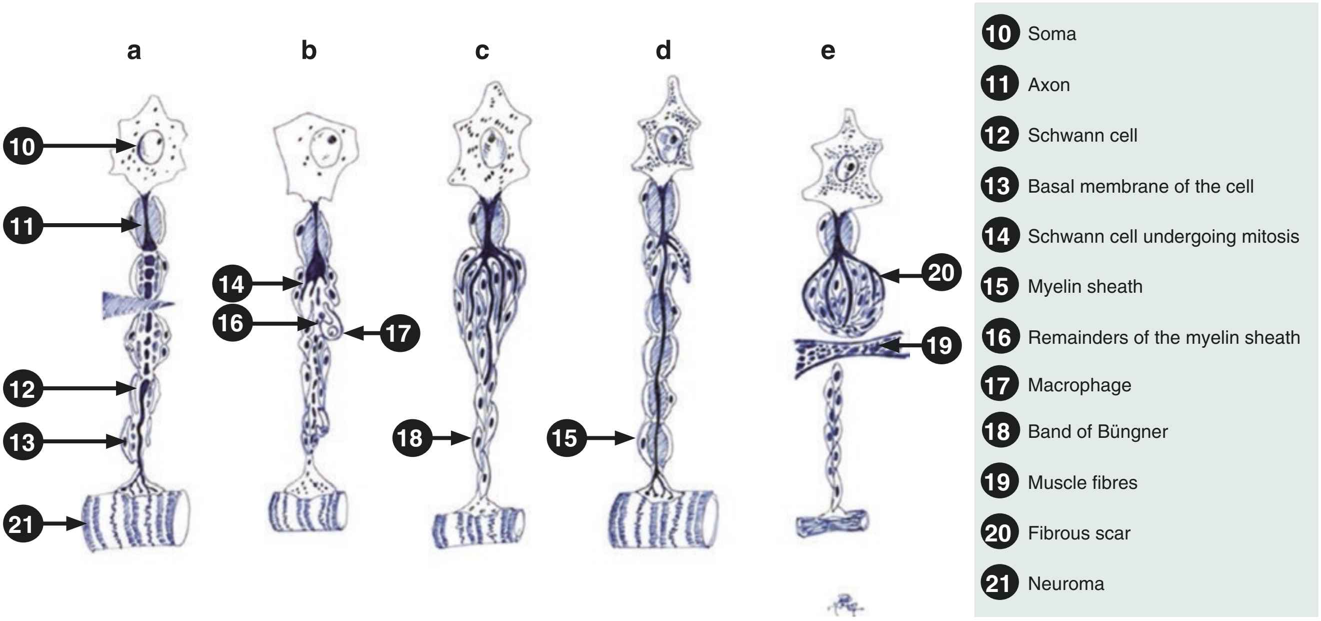
a
b
c
d
e
10
11
14
16
17
12
13
21
18
15
20
19
10 Soma
11 Axon
12 Schwann cell
13 Basal membrane of the cell
14 Schwann cell undergoing mitosis
15 Myelin sheath
16 Remainders of the myelin sheath
17 Macrophage
18 Band of Büngner
19 Muscle fibres
20 Fibrous scar
21 Neuroma

Figure 4. Various types of axon degeneration.

Mechanisms of Neural Repair

In acute trauma, regeneration only begins at the end of the Wallerian degeneration phase, whilst in moderate injuries the process begins nearly immediately. A chain of events follow the trauma, involving neurotrophic factors and cell signalling molecules. Schwann cells have an essential role: firstly, by intensifying the synthesis of adhesion molecules to their surface and by favouring the growth of extracellular protein matrix and, secondly, by activating certain genes by means of neurotrophic factors linking themselves to tyrosine kinase receptors.

Axonal Sprouting

When an injury afflicts the peripheral nerve, an axon sprouts back from the proximal segment towards the currently degenerating distal fragment, colonizing it by tunnelling in order to reach the synapse again, and this way form a new nerve termination. Thus, motor neurons can constitute not only a new NMJ but also synapses of the three types of the PNS axons (motor, sensory and autonomous system).

The main mechanism involved is represented by axonal sprouting. It allows surviving motor neurons to increase the size of their motor unit (MU) (including the motor neuron and all the muscle fibres innervated by it), reinnervating the denervated muscle fibres to reach several times the size of a normal MU. However, when there is only 20% functional MU, the expanding capacity of the MU is insufficient to reinnervate all the denervated muscle fibres: an amyotrophy then takes place.

Axonal sprouting allows for the apparition of thin axonal ramifications coming from healthy axons. It starts at the level of the proximal extremity of damaged fibres, generally in the first hours after the trauma, but sometimes there can be several days before the cellular prolongation appears from the damaged proximal extremity. A growth cone forms at the extremity of the regenerating axon. It is a specialized apparatus, with motility abilities, endowed with “exploration” properties. The scar tissue’s characteristics at the level of the damaged area, if unfavourable, can prevent the axon from reaching the distal extremity, getting lost in the conjunctive tissue and growing chaotically to form a neuroma in the region of the proximal stump. Some axons can nevertheless get through the scar, forming a neuroma called “neuroma-in-continuity”.

Three categories of axonal sprouting are defined according to their function at the level of the emerging sprout: the “ultra-terminal” sprouting which guides the axonal sprout towards the NMJs (Figure 5a) with a base emerging from the main axon just before its blooming in the synapses, the preterminal sprouting taking its source more distantly from the axonal termination (Figure 5b) and the nodal sprouting at the level of the nodes of Ranvier (Figure 5c). An intense axonal germination becomes necessary when more than 85% of the motor neurons have been destroyed and remains random when only 20% of these have subsisted. In extreme cases, a single axon can then emit several types of sprouting (Figure 5d). The capacity of motor neurons to increase the number of muscle fibres within their MU, thanks to axonal sprouting by a factor of 3–8, was demonstrated by electrophysiological tests. Furthermore, it has been demonstrated that even though there is a diminution of the number of MU during denervations, the remaining MUs are compensated by an increase of contractility proportional to the degree of denervation.

Axonal sprouting is a crucial parameter to consider when trying to understand the pathophysiological mechanisms that are responsible for motor neuron loss, but also in clinical implications that it can create in the context of various pathologies such as polymyelitis, amyotrophic lateral sclerosis, partial nerve injuries or even functional denervations.

Despite the attempts of motor compensation involved in these pathologies, it has been clearly demonstrated that an absence of activity, or on the contrary a neuromuscular activity that is too intense, is harmful to axonal sprouting in the patient’s partially denervated muscles.

The understanding of these mechanisms at the base of these contradictory effects has led more recently to a suggestion of reeducation strategies for patients based on moderate muscular mobilizations, favouring axonal sprouting and optimizing perhaps a potential functional regeneration.

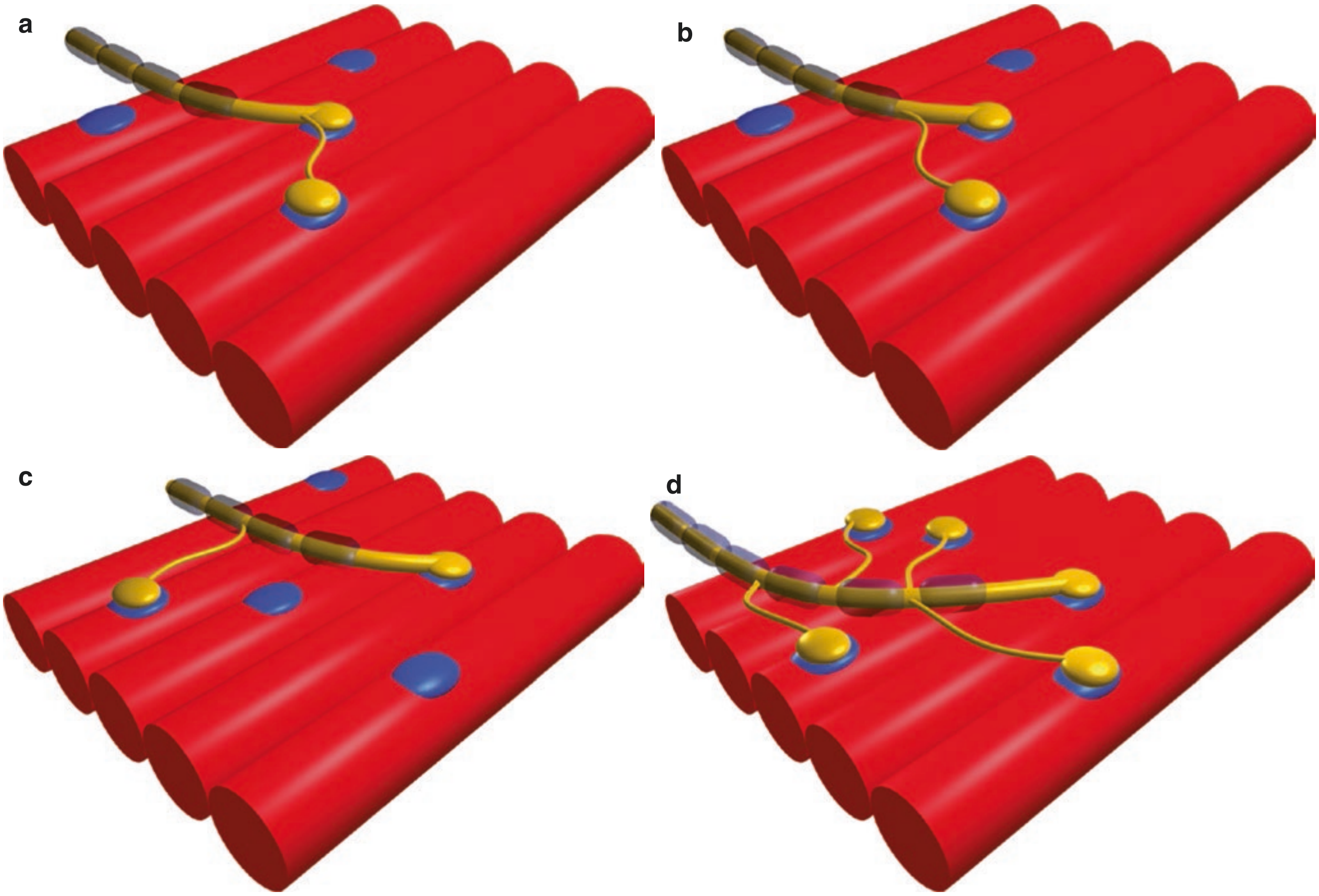

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Figure 5. Axonal sprouting (According to Tam et al. (2001)).

A : Extension coming from the main axon before expansion into the synaptic gutters.	**B** : Preterminal Sprouting emerging remotely from the axonal terminal.
C : Nodal sprouting in relation to the nodes of Ranvier.	**D** : One axon can therefore emit several types of sproutings.

Neurotrophic Factors

The smooth progress of degeneration/regeneration processes requires a sophisticated cellular communication system, triggering complex cellular signalization spates, as well as an elaborate trophic and tropic system, similar to those of the inflammatory processes. Factors such as the NGF (neurotrophic growth factor) or BDNF (brain-derived neurotrophic factor) and many others have been identified and participate to its cellular survival and sustenance in normal conditions. NGF, for example, is modulated in an extremely dynamic way by the target of the peripheral nerve and then transported at the soma's level by the retrograde axonal flow. Its concentration at the soma's level diminishes during an injury. It could be the molecular factor triggering regeneration processes. These neurotrophic factors are linked to specific receptors that transmit the cell signalization and regulate the activation of many genes. For instance, we can find these receptors on Schwann cells forming bands of Bungner, the concentration of which increases after an injury. They are themselves subjected to complex regulation mechanisms. NGF is also found in the growth cone and transmitted to the soma in a retrograde way, thus continually stimulating axonal growth, as well as guiding it by an interaction with Schwann cells.

Potential Functional Consequences

Axonal regeneration does not imply a functional restitutio ad integrum. It ends with a maturation process within the new axon at a lower speed than its first growth phase and can last up to a year. Remyelination follows a similar scenario to the one observed during the development leading to an alignment of Schwann cells that wrap around each axon of a myelin sheath with multiple layers. It begins within 2 weeks after axonal regeneration.

Functional Regeneration

It does not necessarily need a perfect regeneration of the nerve's architecture. However, the effects of a prolonged denervation, significantly altering the functional regeneration, are proportional to its evolution period. They are linked to nerve regeneration difficulties but also to the modifications of the target at the peripheral and central levels (neuroplasticity) . The key factor of nerve regeneration is the conservation of basal membranes. Even in the case of significant motor regeneration, the functional result is hampered by concomitant sensory deficiencies, especially proprioceptive. Sensory receptors can persist after a year and allow functional reconnections. The sensory scheme is relatively well conserved in first- and second-degree injuries, thanks to the connections from the correct axons to correct receptors. After more acute injuries and nerve regeneration, sensory regeneration is always incomplete. Finally, let us highlight the very poor possibility of regeneration of vegetative fibres. Many factors participate to this phenomenon: notably the impossibility for some axons to gain their receptors back, the existence of crossed reinnervations, and a possible degradation of some receptors, or some cortical modifications linked to neuroplasticity.

Neuroplasticity

Peripheral nerve injuries and their regeneration cause functional modifications of the corresponding cortical areas. These modifications can be found at the level of the thalamic projections, the brain stems and probably at the medullary level following a sequence that remains unknown. This phenomenon is a part of cerebral plasticity. The recovery will be complete if the denervated area is minor or limited and if it is wider, with silent residual cortical areas. The end of these substitution and reorganization cycles is divided into two phases: a precocious first phase of quick reactivation within a few hours and then a second, slower phase. The same mechanisms can be observed on the motor facet. In peripheral nerve injuries, there are sensory modifications caused by cortical modifications: irrational sensations due to substitutions of impulses and over-representation of adjacent areas generating hyperpathia, troubles of localization, astereognosis and hypersensibility (hyperesthesia, hyperpathia and dysesthesia). Phantom limb pain finds some of its anatomical substrate in these rearrangements. The peripheral nerve's regeneration, incomplete, will once again disturb this organization. The taking over of these projection areas will generally remain incomplete, even after a long evolution period. It is more often than not chaotic, in patches; some reinnervated areas can have several representations or none at all. These representations can be misplaced. The last reorganization leads to a cortical representation that is smaller and disharmonious, conserving patches of representation in adjacent areas. This territorial compromise is the source of dysfunctions.

Conclusion

The peripheral nerve's reaction to an injury is unique and differs from the one encountered at the level of the central nervous system. It takes place according to a complex process of degeneration and regeneration that remains to this day only partially elucidated. The molecular and cellular biology's progresses bring additional hope towards future therapeutic and medico-surgical advances in taking charge of peripheral nerve injuries, optimising the already astounding abilities of spontaneous regeneration. Perhaps they will also allow researchers to better understand why the central nervous system does not possess such properties and bring stimulation and regeneration strategies in the neuraxis as well as in the peripheral nervous system.

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Data Learned from Embryology

Embryological Development of the Peripheral Nerves

Two phases are distinguished in the development of peripheral nerves: the growth of precursor cells and the development of segmental spinal nerves.

Growth of Precursor Cells

The axons of the motor neurons in the anterior horn leave the neural tube when the first striated muscle fibres appear in the myotome through cell fusion. The growing axons have a growth cone at their extremity on which pseudopods are constantly developing. These pseudopods attempt to find a way between the sclerotome's cells until they reach a muscle fibre with which they can form a synapse (Figure 1). The next axons change the direction of their growth cone according to the slightly more advanced precursor fibres, which improves their chances of reaching their terminal organ. Axons directed in the wrong direction or supernumerary that cannot find yet to be innervated muscle fibre will degenerate. The sensitive spinal ganglion cells' peripheral axons establish a link with motor nerve fibres whilst the central axons form synapses with the central neurons of the alar lamina. Ventral axons follow the myoblasts that migrate in the ventral abdominal wall and in the buds at the extremities. Synapses are formed when these myoblasts become myotubes (Figure 1).

Development of Segmental Spinal Nerves

Basal Lamina and Alar Lamina

During neural differentiation, the ectoderm layer thickens and determines the shape of the neural tube. The ventral bulge of the sheath corresponds to the basal plate, whilst the dorsal bulge corresponds to the alar plate. The basal and alar laminae evaginate in the ependymal canal, so that a neural fold appears between them. The motor neurons of the anterior horn are situated in the basal plate, from which the axons leave the future spinal cord by the anterior root. The sensitive neurons are situated in the alar plate on which the afferent axons coming from the spinal ganglia cells end.

Peripheral Nerve Pathways

The precursor fibres that have reached their target determine the progression pathway of the spinal nerves' axons. They carry the following axons taking the shortest path towards the target cells that came from somites. Each somite has a corresponding spinal nerve. The axons form a ventral motor root and a dorsal sensitive root, as well as a dorsal branch for the dorsal muscles and a ventral branch for the ventral muscles and the corresponding skin areas.

Formation of the Myelin Sheath

The auxiliary cells of the axons (Schwann cells) of the spinal nerves come from the neural crest. They migrate towards the periphery with the axons through the first-stage spinal ganglion. They form the cells that surround the peripheral nerve fibres by taking axons into a deep invagination of their cell membrane (nonmyelinated fibres). In the myelinated-to-be fibres, the plication of the membrane of the Schwann cell winds itself several times around the axon.

❶ Sensitive neuron
❷ Pioneer fibre
❸ Growth cone
❹ Neural tube
❺ Spinal ganglion
❻ Motor neuron
❼ Myotome
❽ Dorsal root
❾ Ventral root
❿ Alar lamina
⓫ Sulcus limitans
⓬ Basal lamina

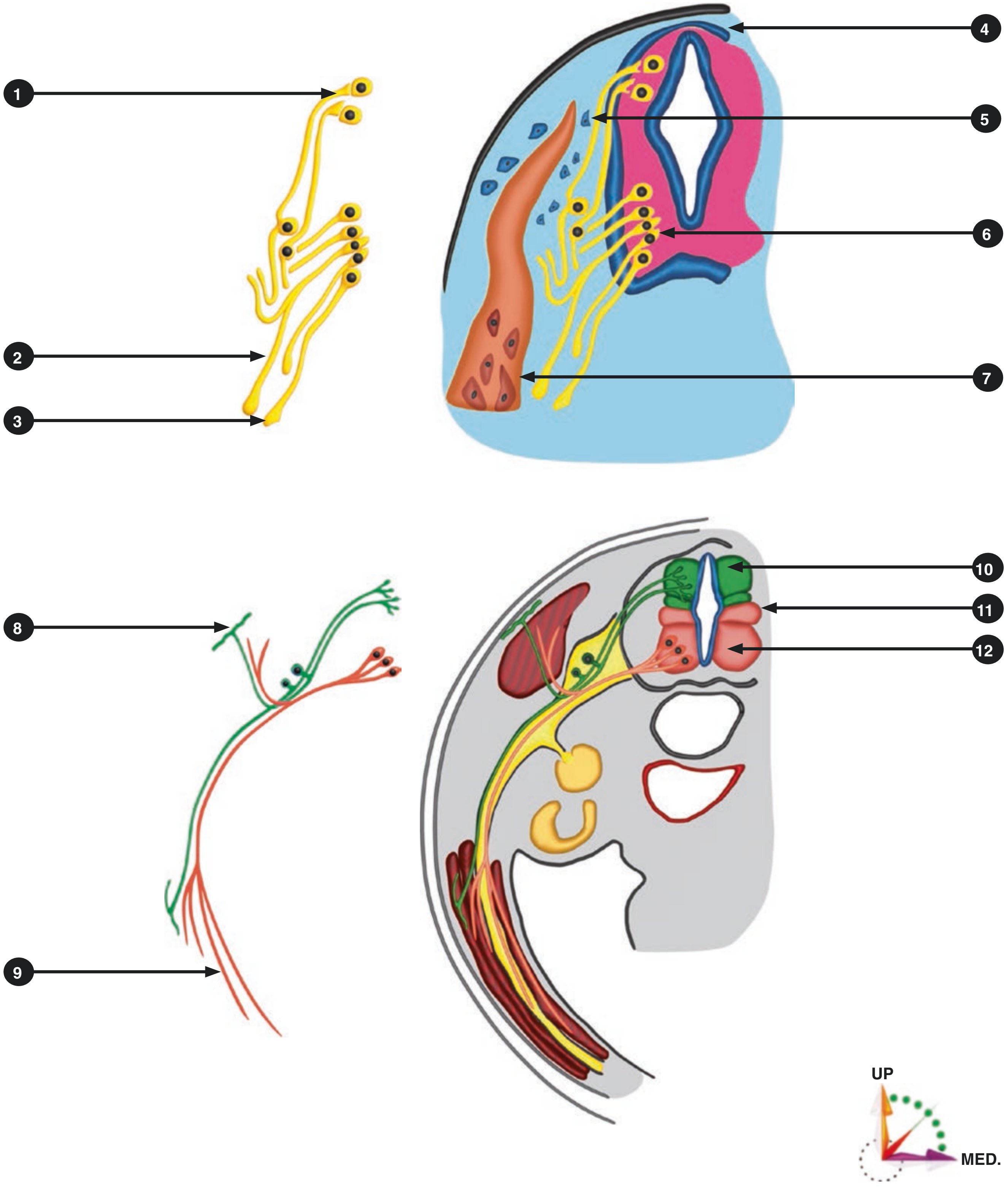
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Figure 1. Growth of the pioneer fibres and development of the secondary spinal nerves.

Development of the Innervation of Limbs

Introduction

The complexity of limb innervation comes from the entwinement of several embryonic and constitutional factors. It is the precocity of this innervation and of the connections established between nerves and primitive mesenchymal condensations, which would actually be the origin of the differentiation of muscle groups.

This innervation begins in a synchronous way with the formation of the limb buds. Several embryogenesis classifications are established one after the other according to the development's evolution. The stages of Blechschmidt begin after 23–26 days of embryogenesis (Figure 2).

Notion of Motor Innervation

Just after the beginning of neurulation, at about 5 weeks of development, the nerves grow in the limb buds from the outline of a plexus constituted by contiguous spinal nerves. The division of the primitive muscle mass by the sclerotome (first signs of bones) in two muscle groups also leads to a division of the nerves in two independent groups. The division of the nerves in dorsal branches corresponds to the dorsal extensor muscle groups, whilst the division of the nerves in ventral branches corresponds to the ventral flexor muscle groups. As they migrate, the outlines of muscles carry their innervation. Thus, in a general manner, the majority of muscles keep an innervation known as "original".

Notion of Cutaneous Innervation

In the embryo, cutaneous innervation is spread on the walls of the trunk in segmental bands called dermatomes.

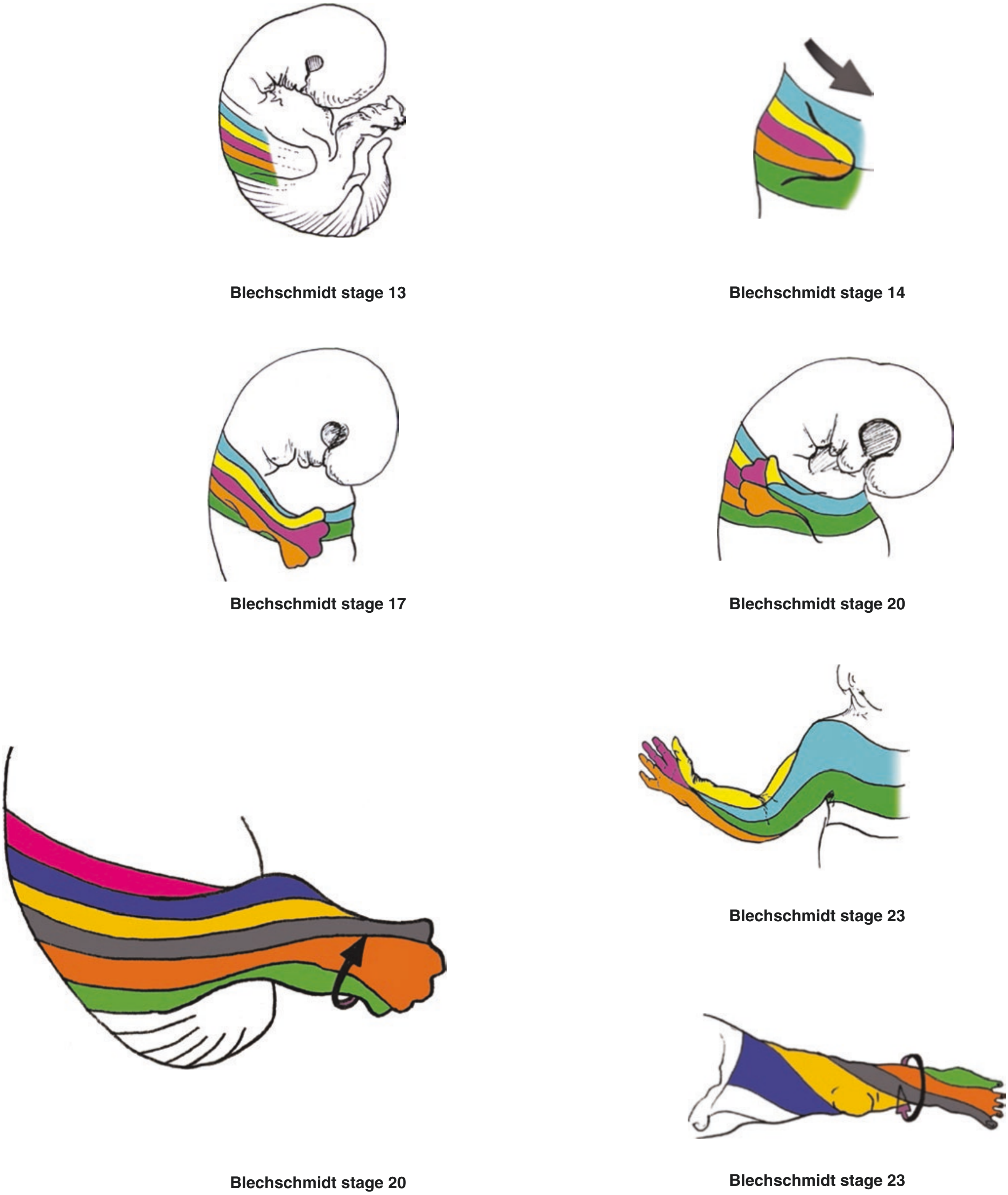
When the limb buds appear, the dermatomes that cover them begin to change. They increase in length and evaginate from the trunk, which in the end excludes them from the innervation of the soon-to-be thoracoabdominal wall.

In 1893, an English physiologist, Dr. Sherrington, experimentally demonstrated that a single cutaneous area is innervated by several dorsal rami in monkeys. In humans, dermatomes were first highlighted in pathologies. Henry Head showed that a zoster-like infection caused a skin rash and a hyperalgesia on a very precise area observed in an identical way in several subjects.

Several years after, in 1933, Foerster provided a remarkable description of dermatomes based on surgical sections of different dorsal rami during the first surgeries on spastic patients and the analysis of nerve injury cases linked to tumours or other causes. His dermatome mapping closely corresponded to the one suggested by Head a few years before and by Sherrington in monkeys. Keegan and Garrett later revised Foerster's anatomical description. Their description is based on noticing that a compressive disc herniation causes hypoesthesia in a precise area, relatively constant and coherent with the previously described notion of dermatome. The basic premise claimed that such compression was monoradicular. Their description is still used in many recent publications.

This consequence of limb development explains why the C4 dermatome is immediately adjacent to the T2 dermatome at the level of the thoracic wall and why the L2 and S3 dermatomes are also more caudally contiguous. The intermediate dermatomes between C5 and T1 are in charge of the innervation of upper limbs. The intermediate dermatomes between L3 and S2 are in charge of the innervation of the extremities of lower limbs.

At the level of limb formation, the somite migration is more complex because of a torsion phenomenon responsible for the rotation of dermatomes innervating the lower limbs and evolving in parallel with the extremities transformation, in a synchronous way.



Blechschmidt stage 13

Blechschmidt stage 14

Blechschmidt stage 17

Blechschmidt stage 20

Blechschmidt stage 20

Blechschmidt stage 23

Blechschmidt stage 23

Figure 2. Embryogenesis and first steps of dermatome development in human embryo (According to Blechschmidt et al. (2011)).

Innervation of the Limbs in Adults

Origin and Constitution of the Limb Nerves

The limb nerves come from spinal nerves, linked to the neuraxis by two roots, the anterior motor root and posterior sensitive root; there are therefore two types of radicular innervation:

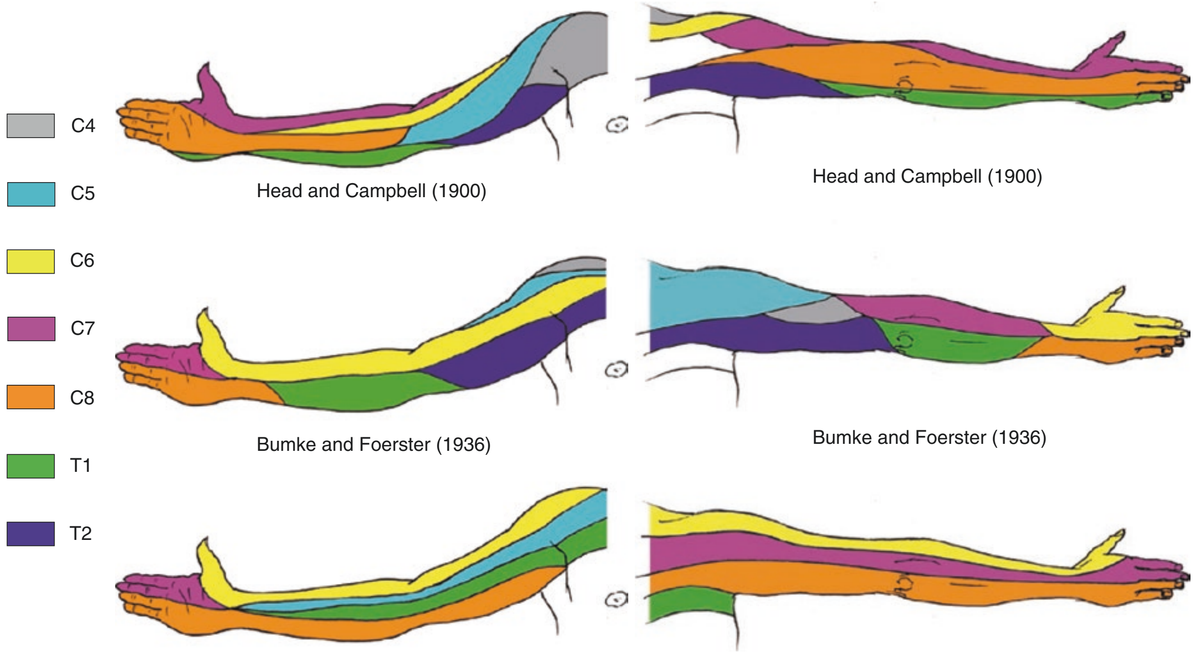
- Motor radicular innervation for muscle groups of shared origin. Each muscle generally receives its motor innervation from several spinal nerves, which explains why a radicular lesion rarely causes a complete motor paralysis.
- Sensitive radicular innervation corresponding to a precise cutaneous area, also called dermatome.

According to their location, the innervation area of spinal nerves may or may not keep a metameric disposition on the whole.

The dorsal and ventral rami headed for the trunk keep a metameric organisation. In contrast, the branches destined to the limbs see their nerve fibres intertwine at the level of peripheral relay centres that act like genuine shunting yards, constituting the limb plexuses. A limb nerve can therefore come from motor and sensitive nerve fibres coming from different spinal nerves. This explains why the sensitive cutaneous area overlaps that of the adjacent spinal nerves and thus several dermatomes.

When it comes to the distribution of dermatomes in the upper limb, several studies have been performed giving different representations according to authors. Currently, the description most often used is Keegan and Garrett's representation, without forgetting that the difference between each individual remains considerable (Figure 3). It can be especially noticeable that, at the level of sensitive areas, the description of the innervation of the hand is difficult to generalize (Figure 4).

Dermatome representation is paramount in diagnosis of medullary injuries. The sensitive deficit and irritation can generally help locate the injury. However, the dermatomes' bounds



Head and Campbell (1900)

Head and Campbell (1900)

Bumke and Foerster (1936)

Bumke and Foerster (1936)

Keegan and Garrett (1948)

Keegan and Garrett (1948)

Figure 3. Various anatomical representations of the dermatomes of the upper limb.

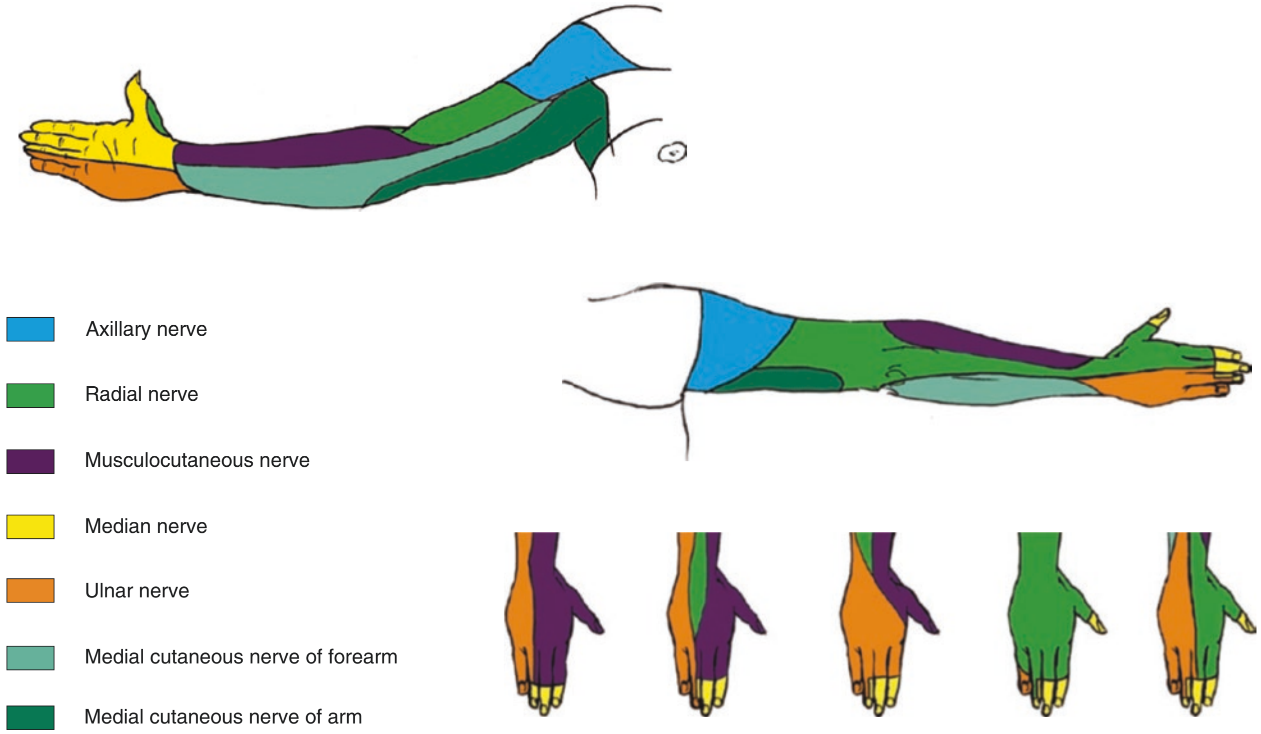

🟦 Axillary nerve
🟩 Radial nerve
🟪 Musculocutaneous nerve
🟨 Median nerve
🟧 Ulnar nerve
Medial cutaneous nerve of forearm
Medial cutaneous nerve of arm

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Figure 4. Sensitive innervation territories of the nerves of the upper limb and its variations in the hand.

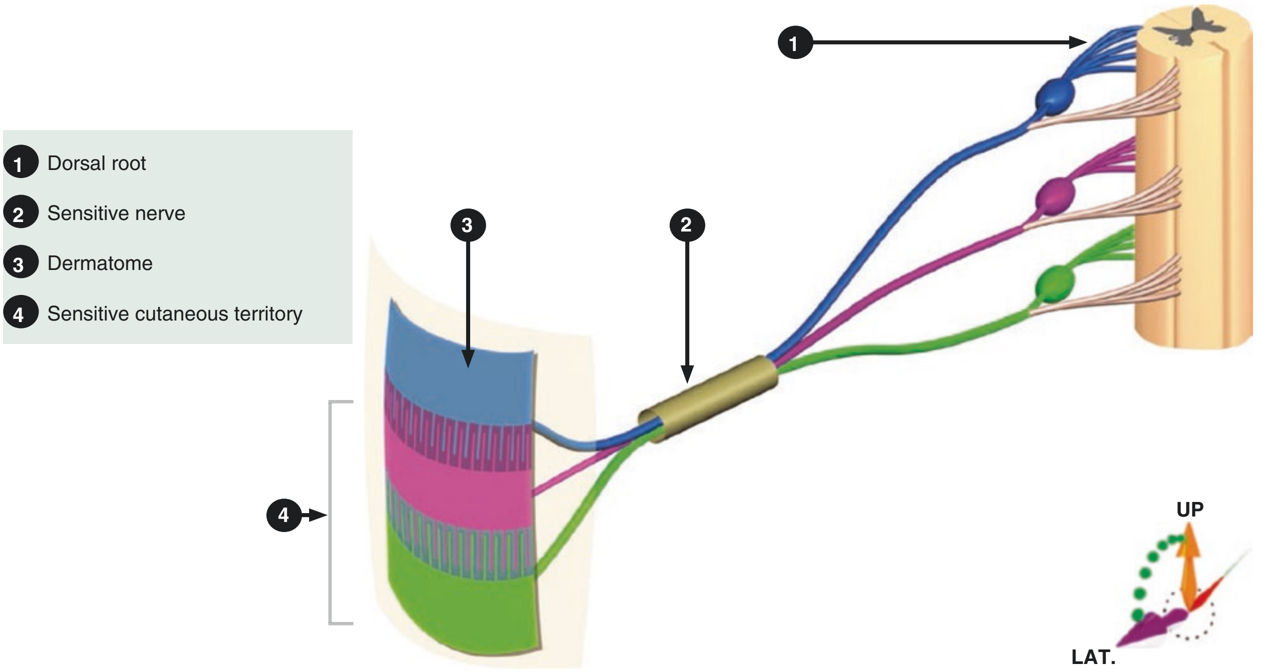
1 Dorsal root
2 Sensitive nerve
3 Dermatome
4 Sensitive cutaneous territory
1
2
3
4
UP
LAT.

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Figure 5. Cutaneous innervation and notion of dermatome.

overlap, which is why there is not always a full agreement between clinical and anatomical descriptions (Figure 5).

When it comes to the lumbar and sacral dermatomes, the first reported observations date from 1886. An English surgeon named William Thorburn based his research on the sensory disorder of patients affected with spinal cord injury. His first observations were about cervical spinal cord injuries and, in 1888, injuries in roots of cauda equina. The article ensuing from these observations was published in 1893, the same year as Sherrington's article. This article only presented lumbar and sacral dermatomes; some roots were not represented.

In the same period, M.A. Starr, an American surgeon, also described his version of lumbar and sacral dermatomes mapping. This version described limits for the anterior face of the lower limb that would evolve in the years that followed, but his posterior face was already a premise of Keegan and Garrett's (1948) study.

Embryological data also get added to these purely anatomical studies in the introduction's extension situated above. These concern the segmental disposition of dermatomes and their overlapping of radicular cutaneous territories (Figures 6 and 7). This disposition in bands corresponds to the development of the dorsal roots of the embryo. They stretch distally from the neuroectoderm. In lower limbs, this development is accompanied by a movement of a medial and inwards torsion and rotation that explains the imperfectly linear disposition of these dermatomes.

Thus, when a nerve root is injured, the resulting hypoesthesia can be completely or partially concealed by substitution of the adjacent territories. The nerve fibres also undergo a "stretching" of the underlying and overlying roots' territories during their embryonic development. The block of a root only induces an incomplete anaesthesia of the corresponding dermatome.

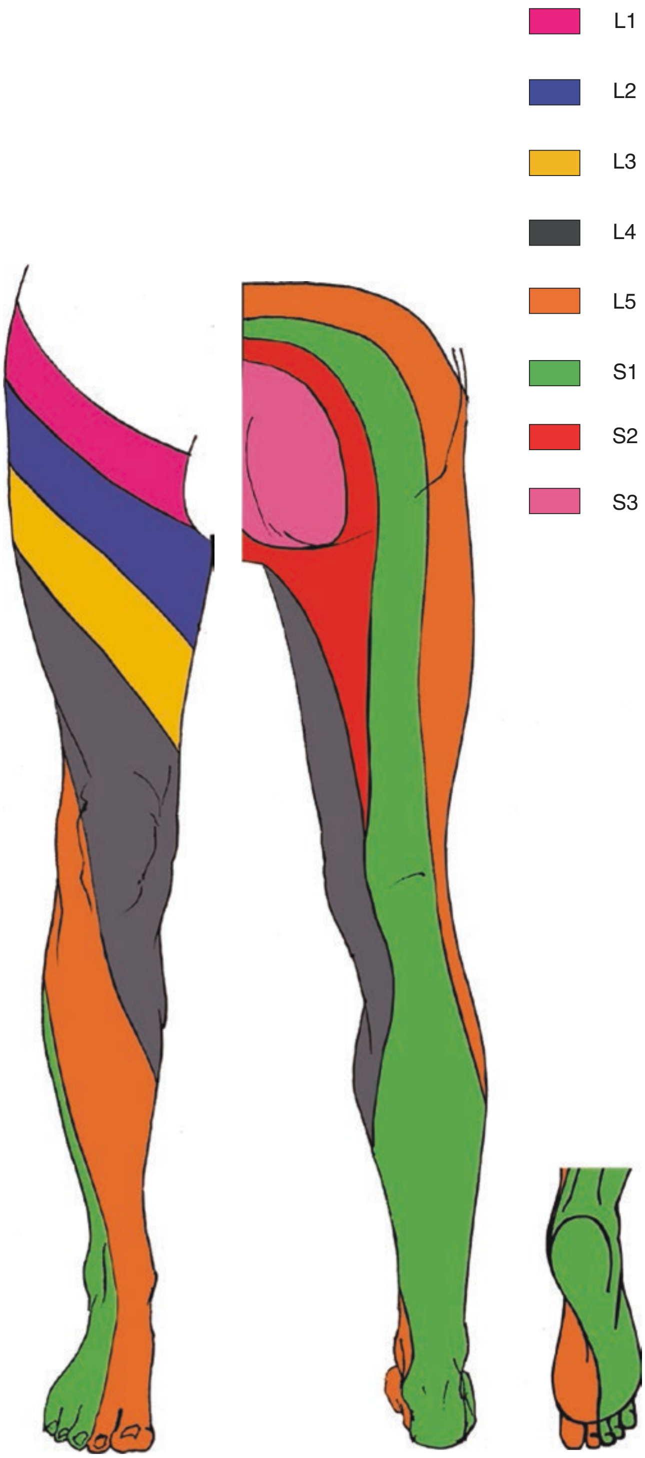

Figure 6. Dermatomes of the lower limb.

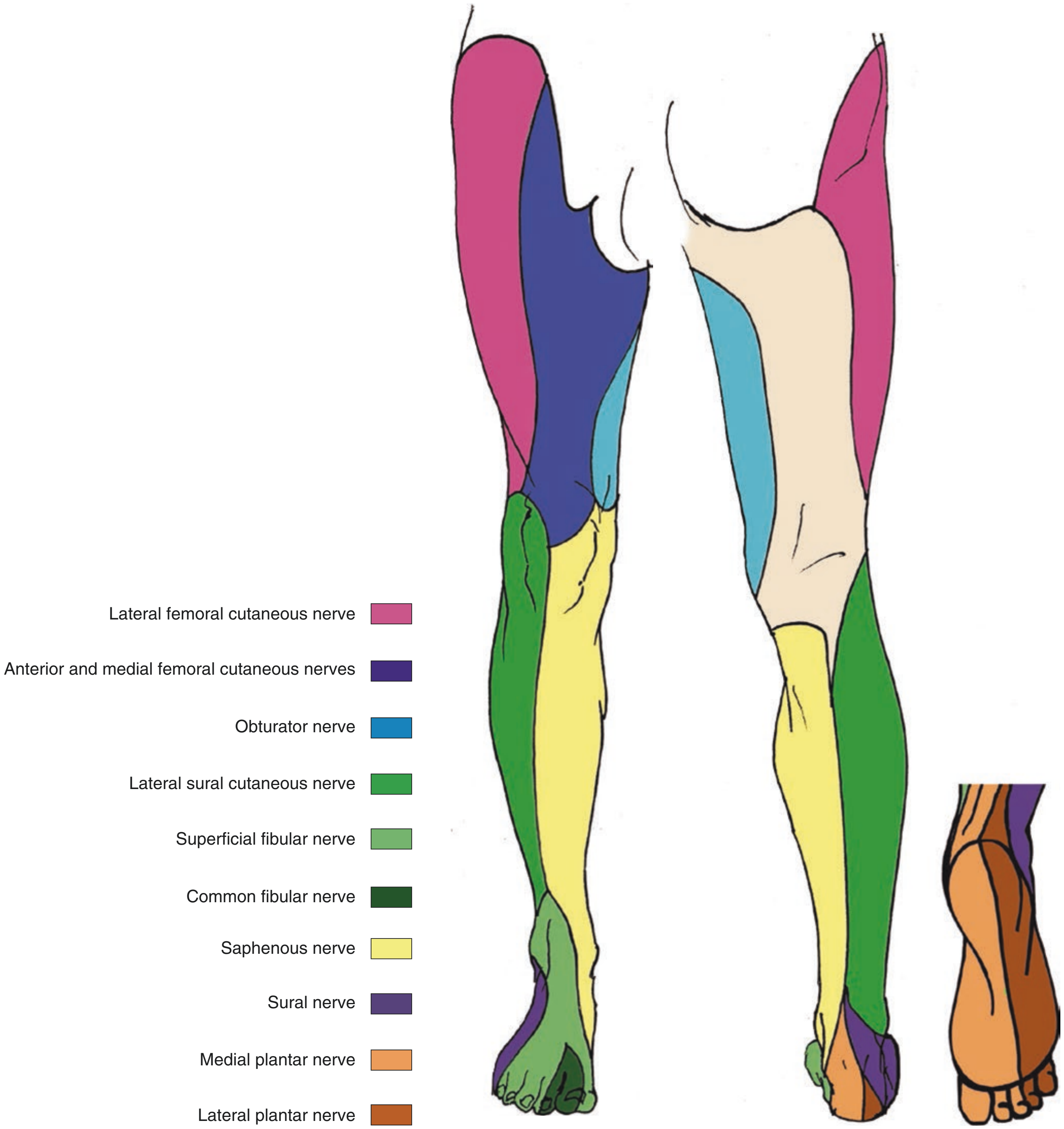
Lateral femoral cutaneous nerve
Anterior and medial femoral cutaneous nerves
Obturator nerve
Lateral sural cutaneous nerve
Superficial fibular nerve
Common fibular nerve
Saphenous nerve
Sural nerve
Medial plantar nerve
Lateral plantar nerve

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Figure 7. Sensitive innervation territories of the lower limb nerves.

The Notion of Plexus

The formation of nerve plexus ensue from the embryological elements mentioned above. The separation of anterior and posterior muscle mass of the limbs during the precocious stages of development defines the predominating flexor or extensor character of a muscle, as well as the adjacent skin to innervate. These muscles are therefore innervated respectively by anterior or posterior divisions of the corresponding muscles.

At the cephalic (preaxial) and caudal (postaxial) limits of the limbs, some muscles can stem at the same time from the anterior and posterior muscle groups. These muscles are therefore innervated by anterior and posterior nerve divisions. A common example is the brachialis muscle that receives branches from both the radial and musculocutaneous nerve.

Thus, from the ventral roots of spinal nerves, the elaborated connections gather together in extensive plexuses, within which a somatotopic projection is precisely defined. Each peripheral nerve coming from these plexuses contains fibres that belong to two, three, four or five ventral rami of spinal nerves (see notion of dermatome). When laid out in tiers along the craniocaudal axis, the cervical plexus, the brachial plexus (Figure 8) and the lumbosacral plexus (Figure 9) are successively found in front and laterally related to the spine. The last two are crucial for limb innervation.

For each plexus, the efferent post-plexus branches more accurately correspond to anterior division branches of the primary trunks that constitute them, from the ventral radicular rami above them. For the brachial plexus, the musculocutaneous nerve, the median nerve and the ulnar nerve are found as post-plexus efferent branches. Nonetheless, the radial and axillary nerves are more likely the result of posterior divisions of the pre-plexus ventral rami coming from C6, C7 and C8 for the brachial plexus. Likewise, in the lower limb, the obturator and tibial nerves begin in the anterior division branches of the ventral rami of the lumbosacral plexus, whilst the fibular nerve is a result of the posterior division branches of the L4, L5, S1 and S2 ventral rami.

A final degree of complexity must be integrated to this notion of plexus. The nerve fibres pertaining to the tibial and fibular nerves, corresponding to anterior and posterior innervation territories, may be found in a common peripheral nerve sheath even though they clearly appear as independent in the post-plexus area, on the back of the pelvis. In this case, they take the trunk of the sciatic nerve until an apparent division at the level of the higher part of the popliteal fossa, although the real division of these fibres is at the level of the buttocks, at the origin of the sciatic trunk.

The knowledge of this muscular and cutaneous distribution resulting from this intertwinement of fibres is paramount for the clinician and the electrophysiologist, in order to accurately determine the level of injury of the affected peripheral nerve (radicular/truncal/distal).

It is interesting to note that this phenomenon is also observed at the level of some cranial nerves, which are the equivalents of spinal nerves in the encephalon. There is, for example, a nerve block, emerging from the laryngeal nucleus of the spinal nerve (XI) at the intracranial level, which then “takes” the sheath of the vagus nerve (X) at the cervical level. A little lower, it finally separates from it to innervate the larynx in a retrograde way, through the recurrent laryngeal nerve, physical branch of the vagus nerve (X) but corresponding to a block of the spinal nerve XI, etc.

This relative complexity associated with the formation of plexus, especially for the brachial and lumbosacral plexuses, unavoidably causes an important variability between individuals. This variability can concern the distribution of ventral rami of the spinal nerves within the peripheral nerves as much as the dorsal rami. In the end, the constitution of the brachial plexus has been described in a highly variable way for decades when it comes to the implication of the C4 to T2 roots.

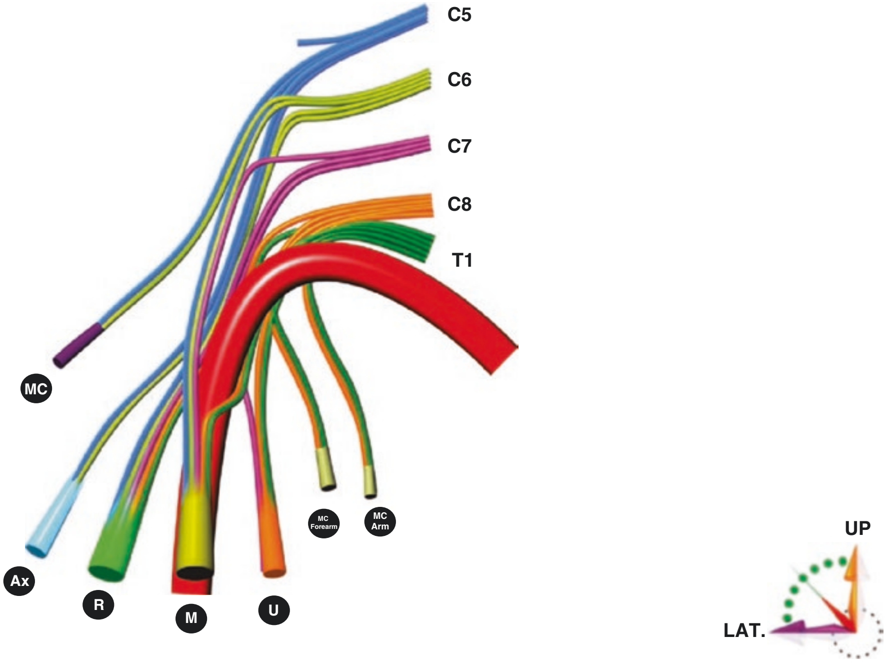
C5
C6
C7
C8
T1
MC
MC Forearm
MC Arm
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Figure 8. Example of a plexus: the brachial plexus.

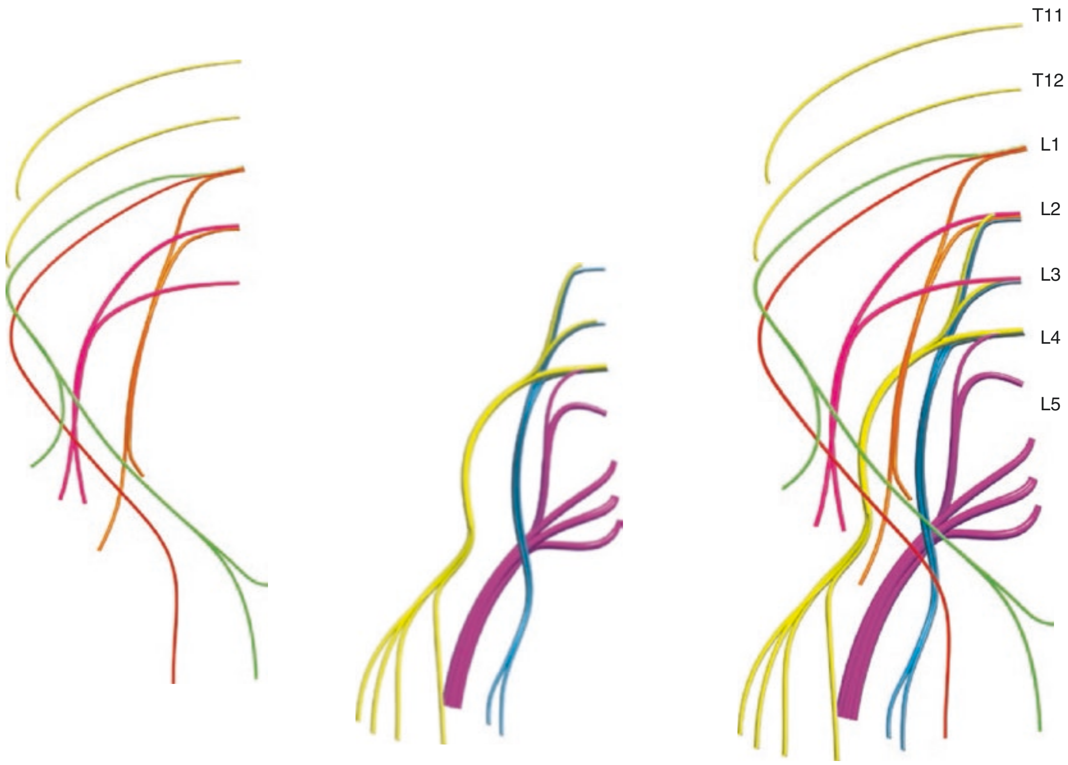
T11
T12
L1
L2
L3
L4
L5

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Figure 9. The lumbosacral plexus.

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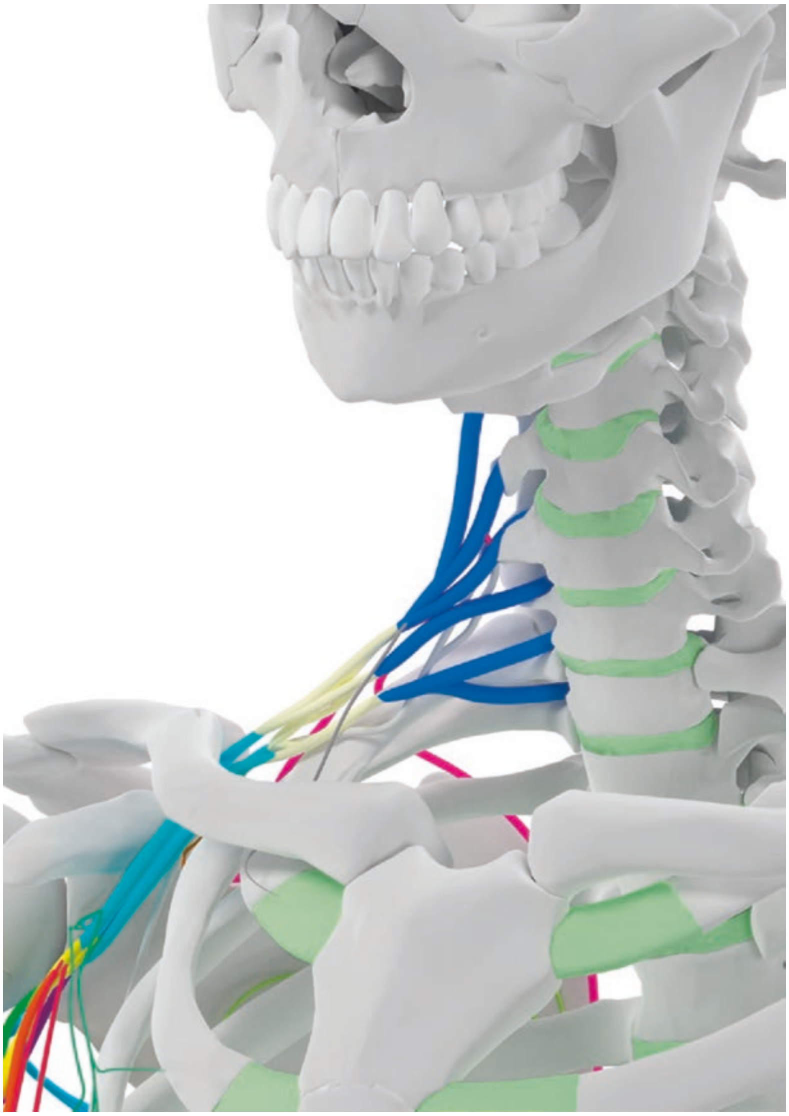
Part II

NERVES OF THE UPPER LIMB

THE BRACHIAL PLEXUS



The Brachial Plexus

Morphological Data

The brachial plexus is charged of the sensitive and motor innervation of the superior limb group. It is constituted of the union of the anterior branches of the last four cervical nerves (C5, C6, C7 and C8) and of the first thoracic nerve root (T1). Sometimes there is a significant amount of fibres coming from C4 or T2. Brachial plexus injuries are frequent in newborn children because of obstetric traction and in young adults mainly because of lower cervical spinal trauma. The plexus brings the spinal roots together in trunks, themselves splitting into divisions and cords.

There are three trunks: the superior trunk coming from the union of the C5 and C6 anterior rami, the middle trunk coming from the C7 anterior ramus and the lower trunk coming from the union of the C8 and T1 anterior rami.

Each trunk splits into two, an anterior division and a posterior division, which then mix their fibres again to constitute cords.

There are three cords: the lateral cord coming from the anterior division of the superior and middle trunks, the medial cord coming from the anterior division of the lower trunk and the posterior cord coming from the posterior divisions of all three trunks. The lateral cord can contain rami from the anterior division of the lower trunk of the brachial plexus or from the posterior division of the superior trunk.

Cords are named after their position from their infraclavicular distribution around the axillary artery.

Peripheral nerves of the upper limbs find their origin in the brachial plexus' cords (Figures BP1 and BP2).

Coming from the lateral cord, there are the musculocutaneous (MC) nerve and the lateral root of the median (M) nerve.

Coming from the medial cord, there are the medial root of the median (M) nerve, the ulnar (U) nerve, the medial cutaneous nerve of the forearm (MC forearm), and the medial cutaneous nerve of the arm (MC arm).

Coming from the posterior cord, there are the radial (R) nerve and axillary (Ax) nerve. At the cervical level, before going under the clavicle, the brachial plexus has several collateral branches:

- Muscle ramifications for the scalene muscles and longus colli muscle.
- The dorsal scapular (DS) nerve, innervating the levator scapulae and rhomboids.
- The long thoracic (LT) nerve, innervating the serratus anterior muscle.
- The nerve to the subclavius, innervating the subclavius muscle.
- The suprascapular (SS) nerve, innervating the supraspinatus and interspinales muscles as well as the shoulder joints.
- On the axillary and thus subclavicular level, the plexus has other collateral branches:
- The medial (MP) and lateral pectoral (LP) nerves.
- The upper (US) and lower subscapular (LS) nerves.
- The thoracodorsal (TD) nerve for the latissimus dorsi.

The brachial plexus has anastomoses with the cervical plexus by the intermediary of C4, with the phrenic nerve (Ph) by the intermediary of C5 and with the autonomic nervous system.

Of note, there are sometimes a significant amount of fibres coming from C4 or T2. According to Harris, when the C4 root supplies fibres to the brachial plexus, the fibres are exclusively coming from the phrenic nerve, coming itself from C4. Several years later, Kerr illustrated several descriptions of brachial plexuses formed with ventral rami of C4 isolated from the phrenic nerve fibres.

The variety found in the descriptions of the brachial plexus only grew as decades passed, but most of them tend in the end to agree with the distribution to which reference is made nowadays. In order to represent the diversity of these interpretations with a few authors, let us note that according to Billet, there were only two primary trunks in the brachial plexus: a superficial trunk situated above a deep trunk. In 1958, Fénard suggested three main formation types of the brachial plexus.

Electronic Supplementary Material The online version of this chapter (https://doi.org/10.1007/978-3-030-49179-6_4) contains supplementary material, which is available to authorized users.

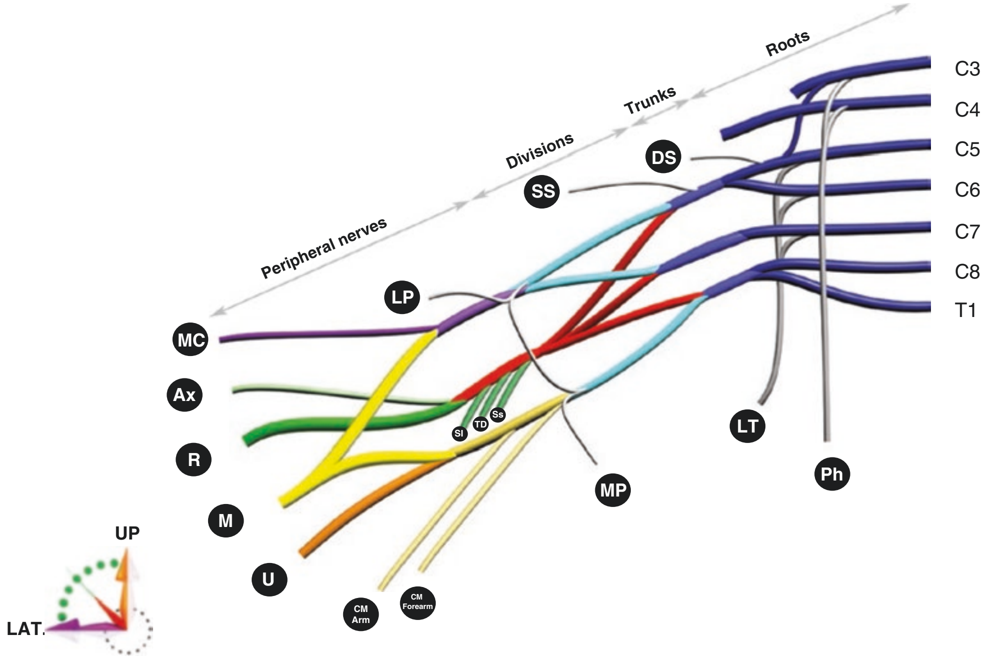

Roots
Trunks
Divisions
Peripheral nerves
C3
C4
C5
C6
C7
C8
T1
DS
SS
LP
MC
Ax
R
M
U
SI
TD
Ss
CM Arm
CM Forearm
MP
LT
Ph
UP
LAT.

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Figure BP1. The brachial plexus: terminal and collateral branches.

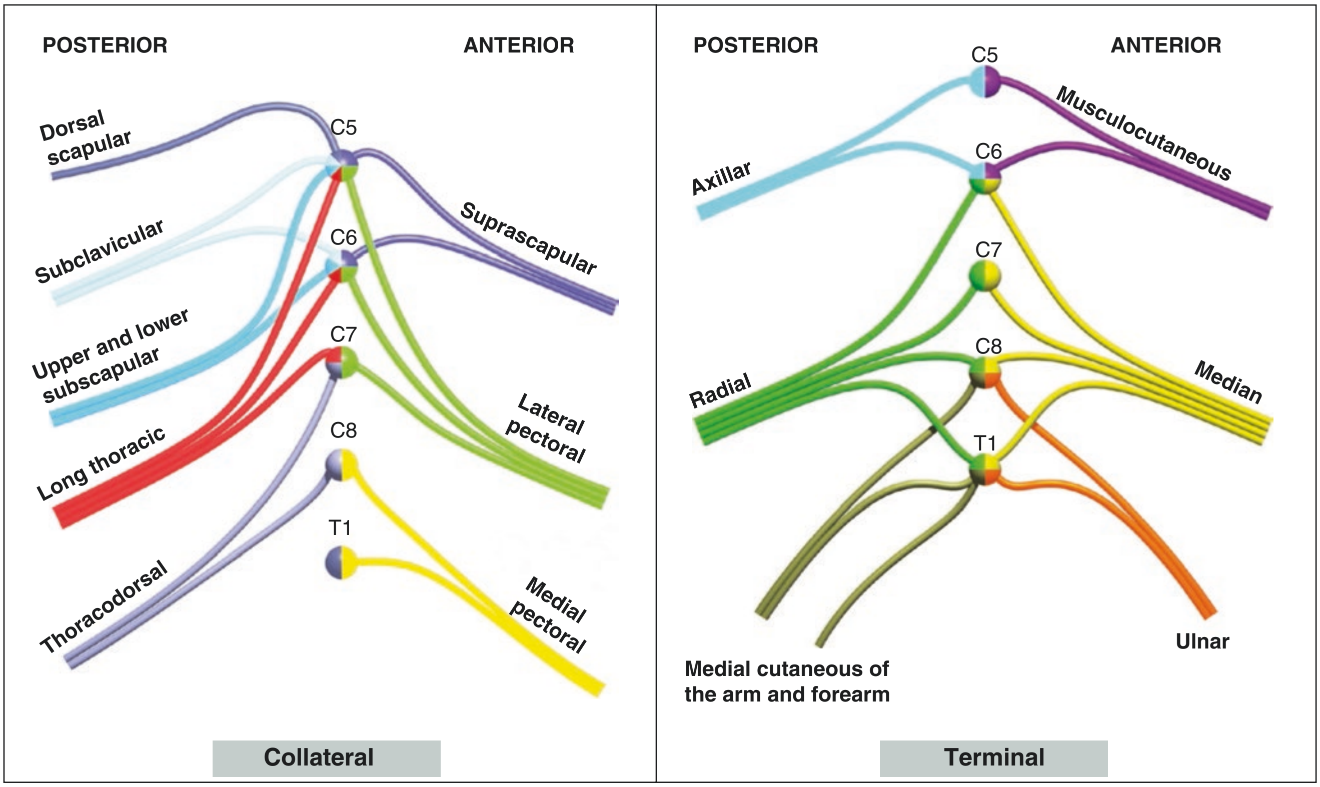
POSTERIOR
ANTERIOR
Dorsal scapular
C5
Subclavicular
C6
Suprascapular
Upper and lower subscapular
C7
Long thoracic
Lateral pectoral
C8
T1
Thoracodorsal
Medial pectoral
Collateral
POSTERIOR
C5
ANTERIOR
Musculocutaneous
Axillar
C6
C7
C8
Radial
Median
T1
Medial cutaneous of the arm and forearm
Ulnar
Terminal

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Figure BP2. *Left diagram*: origin of the collateral branches. *Right diagram*: origin of the terminal branches.

The Brachial Plexus Relations

The brachial plexus is shaped like an hourglass. The junction between its trunks and cords is situated next to and below the clavicle, delimitating a supraclavicular, cervical part and an infraclavicular, axillary part.

At the Supraclavicular Level

The spinal nerves firstly run through the intervertebral foramina area, as delimitated by Testut and Latarjet, with the transverse processes of adjacent vertebrae, the uncovertebral joint underlying ventrally and the superior articular process dorsally. The anterior rami of the spinal nerves then unite in the space between the scalene muscles, delimitated in front by the scalenus anterior muscle and behind by the scalenus medius muscle.

It is important to note that at this level there is a close relationship between the lower trunk (or deep trunk according to Billet) and the first thoracic ganglion. This relation explains why an injury of the lower trunk of the brachial plexus can induce a case of Horner's syndrome.

The plexus comes from the interscalene block where the scalene muscles form the shape of a triangle, in which the anterior limit formed by the scalenus anterior muscle is oblique and the posterior limit formed by the scalenus medius muscle is vertical. It finds its way between the scalenus anterior in front and the scalenus medius and posterior in behind. It faces the apex of the lung and the first rib going downwards. In this area, with the intermediary of the scalenus anterior muscle, it faces the subclavian vein, the subclavius muscle and the omohyoid muscle. The phrenic nerve is not in this area but in front of the scalenus anterior muscle, as it is going down vertically towards the higher opening of the thorax (Figure BP3).

There are a high number of anatomical variations of the scalene muscles. The scalenus anterior and medius muscles' insertion on the first rib can for instance be extended into a fascia. The latter is likely to compress the subclavian artery in case of pathology of the scalene muscles.

These relations are important to take into account when executing anaesthesia of the plexus with supraclavicular access.

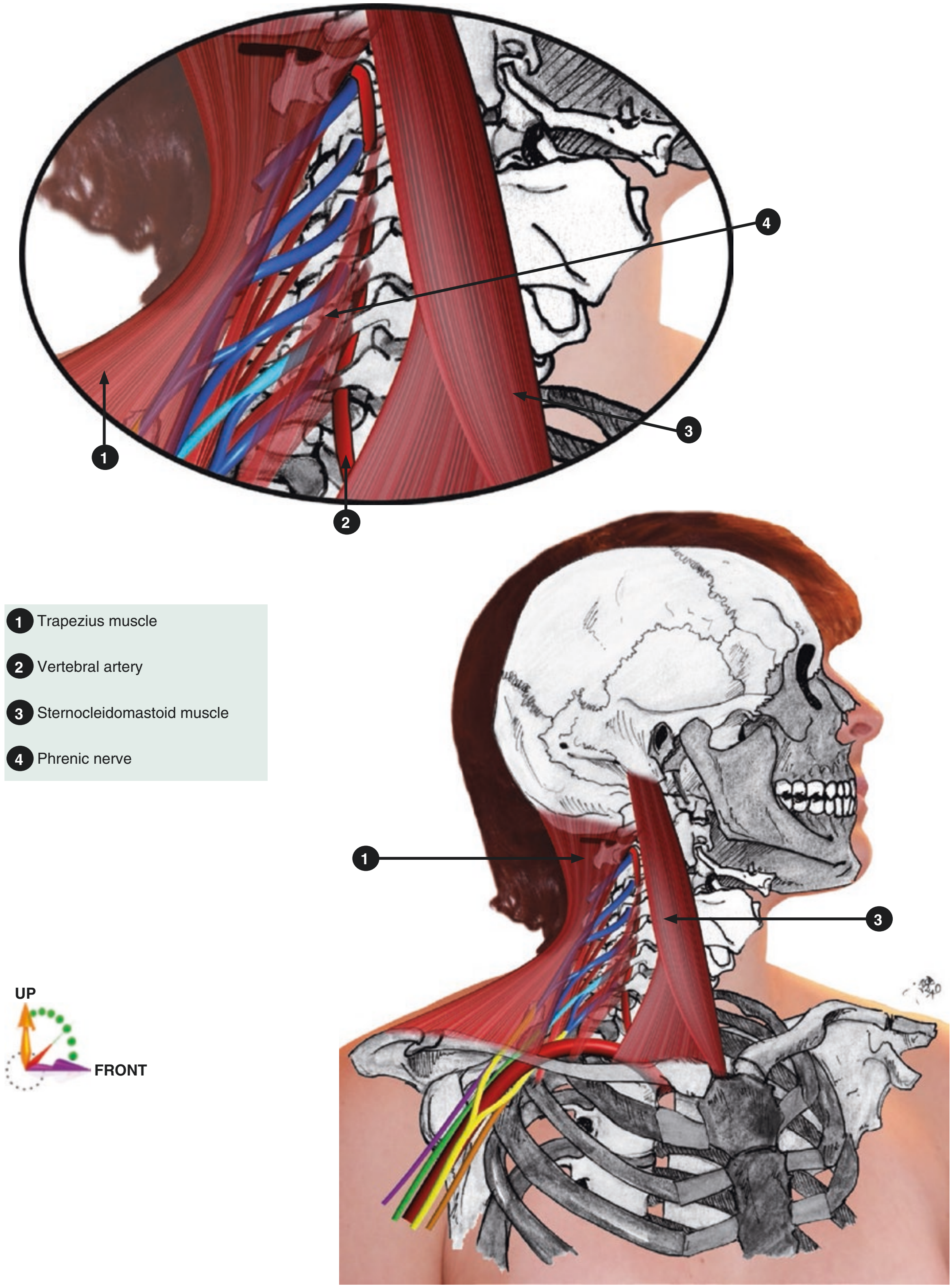

4
3
1
2
1 Trapezius muscle
2 Vertebral artery
3 Sternocleidomastoid muscle
4 Phrenic nerve
1
3
UP
FRONT

Figure BP3. Main relations of the brachial plexus at the cervical level.

At the Infraclavicular Level

In the axillary pit's apex, the plexus finds its way between the clavicle and the subclavius muscle in front and the upper edge of the scapula in behind. It is situated inside the coracoid process and outside of the first rib and of the serratus and scapular area.

In this infraclavicular part of the brachial plexus, trunks split into two types of branches: anterior and posterior. Three cords are thus formed from the latter: lateral, medial and posterior.

At the level of the axillary pit, the cords are situated behind the pectoralis muscles, and their relation with the arterial axillary axis is described by their respective denomination. In front of the descending part of the axillary artery, two branches of the lateral and medial cords join in a "V shape" to form the median nerve, which is the largest terminal branch of the brachial plexus. The pectoralis major muscle and the axillary artery logically constitute the main landmarks that guide local or regional axillary block anaesthesia of the plexus (Figures BP4, BP5, BP6 and BP7).

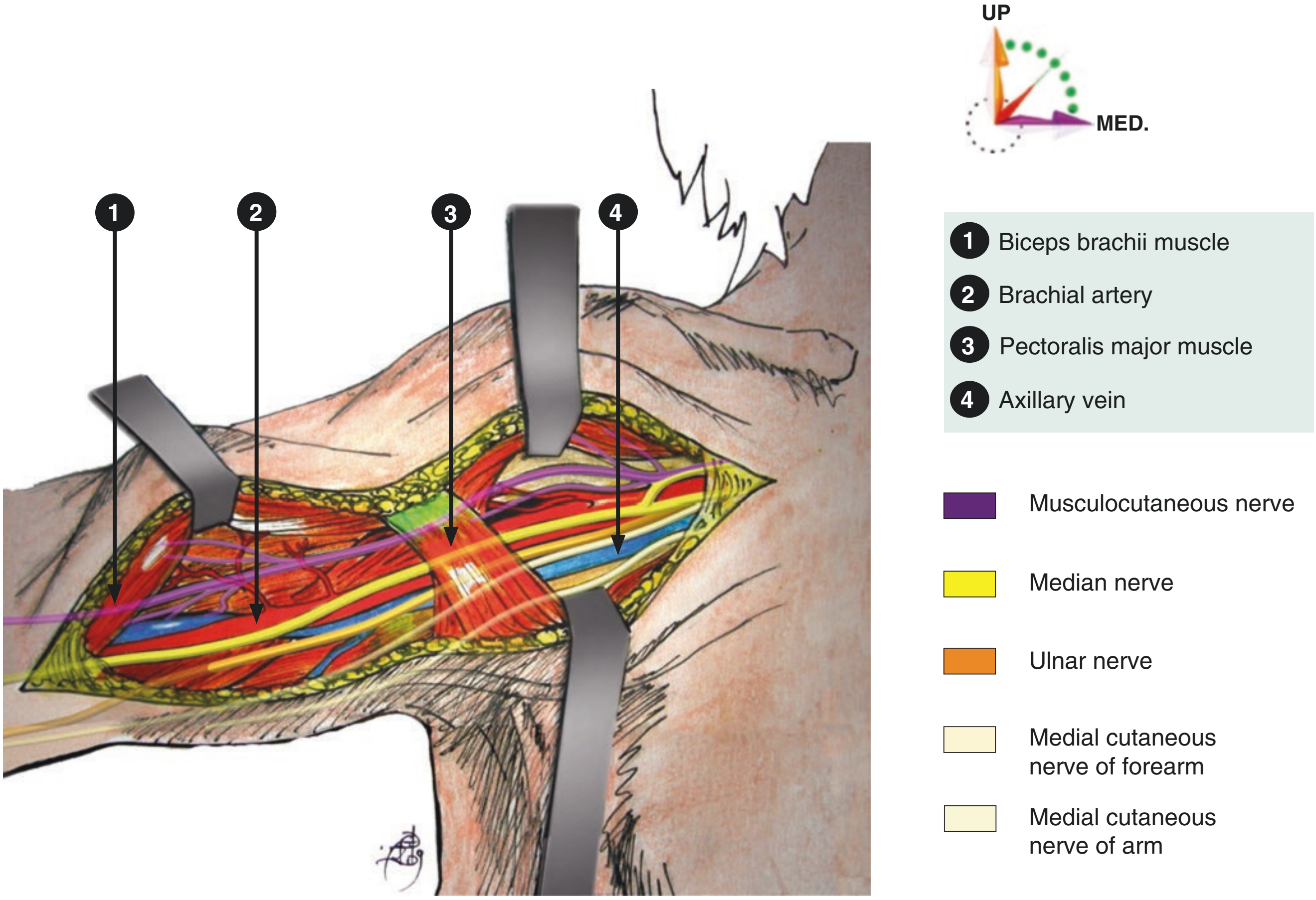

UP
MED.
1
2
3
4
① Biceps brachii muscle
② Brachial artery
③ Pectoralis major muscle
④ Axillary vein
🟪 Musculocutaneous nerve
🟨 Median nerve
🟧 Ulnar nerve
▭ Medial cutaneous nerve of forearm
▭ Medial cutaneous nerve of arm

Figure BP4. Dissection of the axillary fossa and arm (According to Dorn 1992).

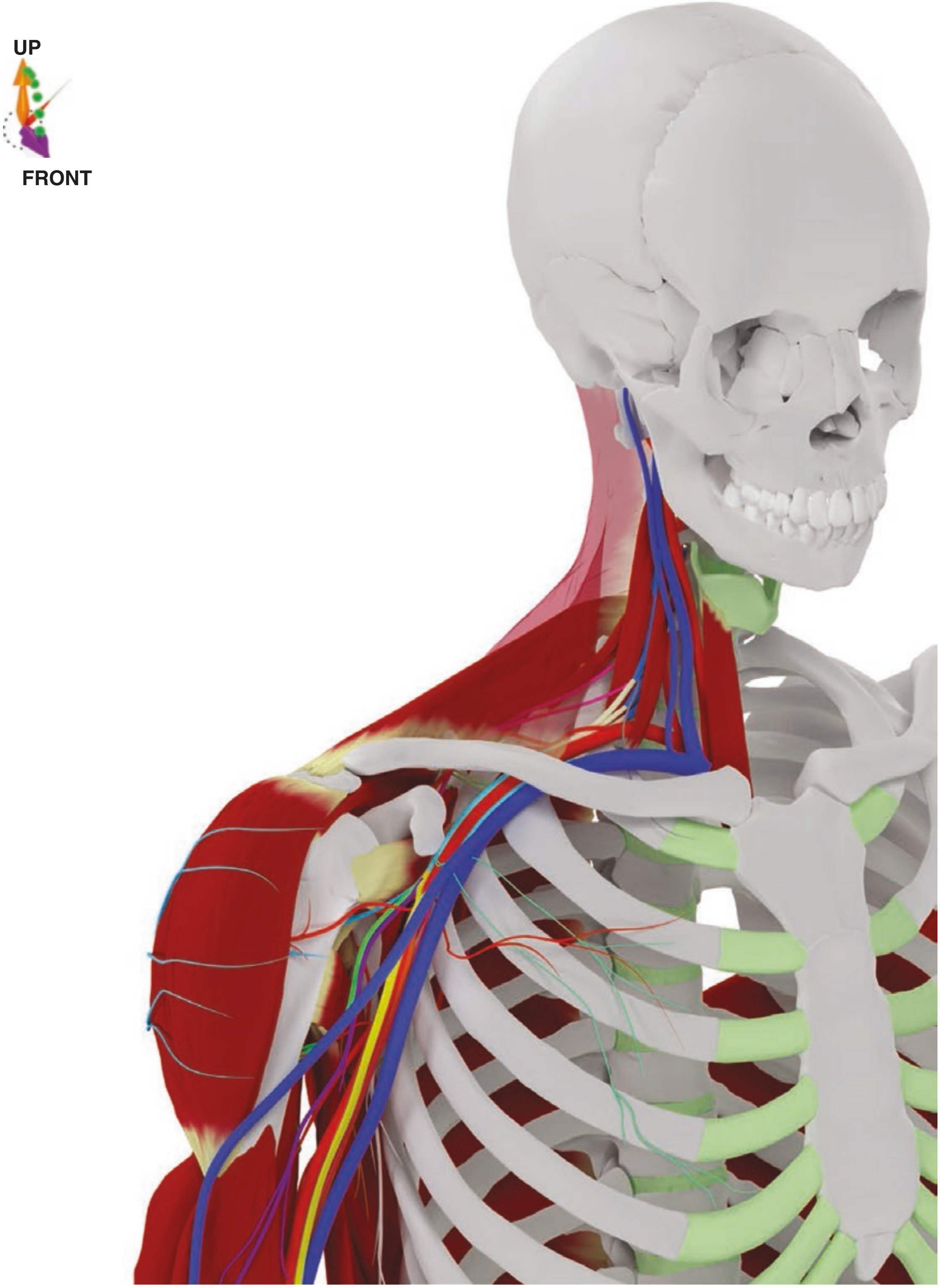
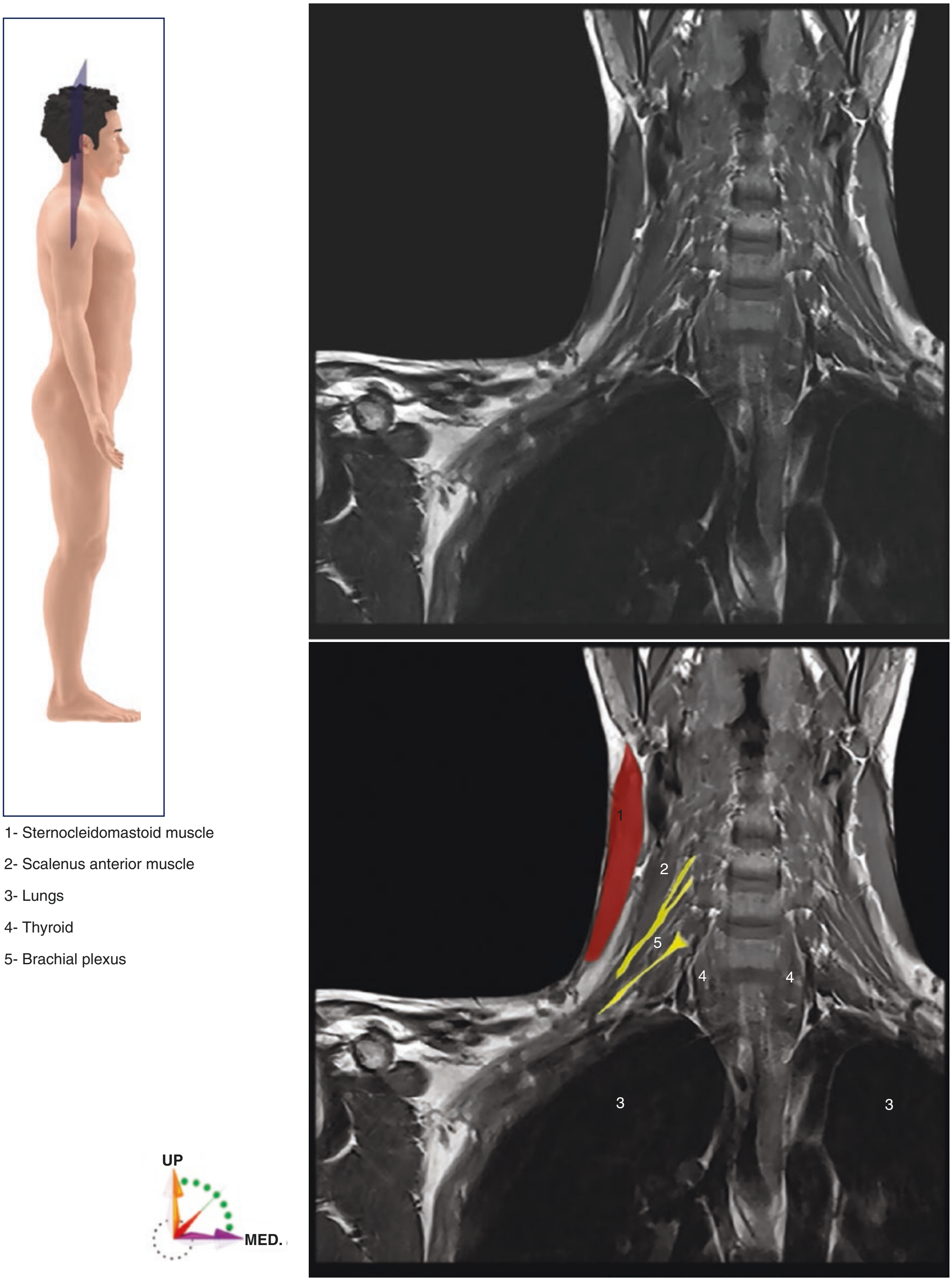


Figure BP5. Relations of the brachial plexus under the clavicle.



1- Sternocleidomastoid muscle

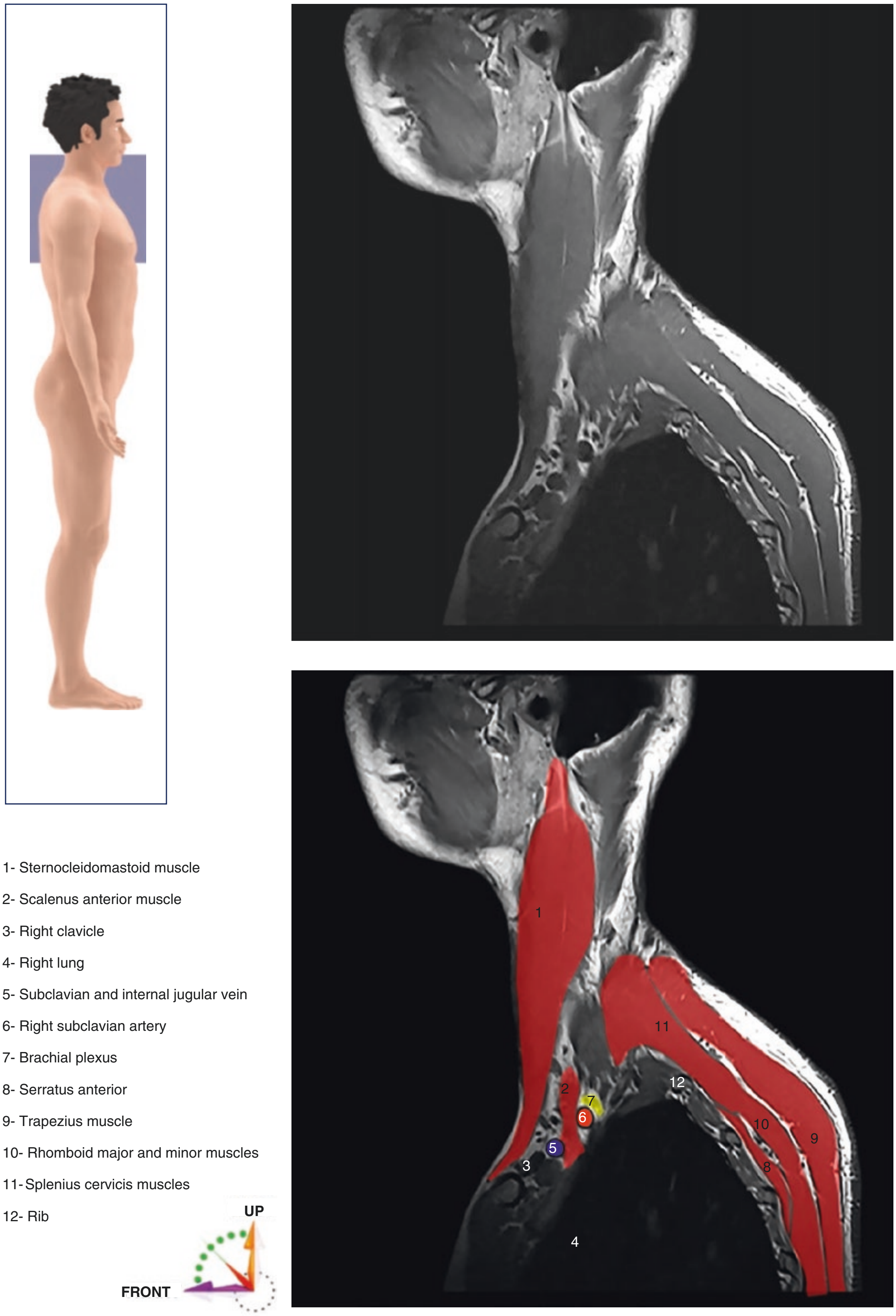
2- Scalenus anterior muscle

3- Lungs

4- Thyroid

5- Brachial plexus

Figure BP6. Coronal MRI scan of the neck and of the axillary fossa, through the brachial plexus.



1- Sternocleidomastoid muscle
2- Scalenus anterior muscle
3- Right clavicle
4- Right lung
5- Subclavian and internal jugular vein
6- Right subclavian artery
7- Brachial plexus
8- Serratus anterior
9- Trapezius muscle
10- Rhomboid major and minor muscles
11- Splenius cervicis muscles
12- Rib

Figure BP7. Parasagittal MRI scan of the brachial plexus showing the neurovascular relations.

Morphological Data: Sono Anatomy

The ultrasound scan is intended to target the nerve roots emerging from the conjugation holes, which are followed by the nerve trunks of the brachial plexus between C4 and T1. The skin markers to be used to position the probe are at the intersection between the horizontal lines passing through the cricoid cartilage and the posterior cervical triangle of the neck.

Ultrasound detection of the apophysis or transverse process of the C6 cervical vertebra, in particular its anterior tuber called "TC" or "Chassaignac tubercle", is initiated.

To ensure that it is not the C5 tuber, time will be taken to make a downward movement to visualize the absence of anterior tuber in the underlying vertebrae. It will then be C7 with certainty.

Depending on the target, it will be possible to start again in the cranial direction to identify the C6 and then the C5 roots, if necessary. We stay at C7 level if this root matches the target.

The nerve root is then identified between the anterior and posterior parts of the transverse gutters.

– Phrenic nerve damage is the great enemy of this technique, which explains why the posterior pathway has historically been preferred in interscalenic anesthesia blocks.

In implanted neurostimulation, the anterior pathway will be preferred, however, for three reasons:

The anchoring of the implanted electrode will be much more stable,

The distance between the electrode and the generator will be shorter and will avoid a loop,

Identification of the phrenic nerve will be possible, especially in neurostimulation of the C5 plexus. Indeed, it is located along the anterior edge of the scalene anterior muscle. It is visible in 93% of subjects.

The use of colour Doppler echography is of crucial importance, as it makes it possible to distinguish the vertebral artery from the cervical roots and also to locate the transverse and suprascapular cervical arteries, which are more inconsistent.

The passage from the vertebral artery to each vertebral foramen above C7 is visualized. It should be noted that in 10% of cases, the vascular structure penetrates the spine only in the transverse foramen of C5 and not in C6, which requires particular vigilance.

Finally, attention should be paid to the possible intramuscular ectopic crossing of the roots, which will require an intermuscular plan when neurostimulation techniques are considered (see below).

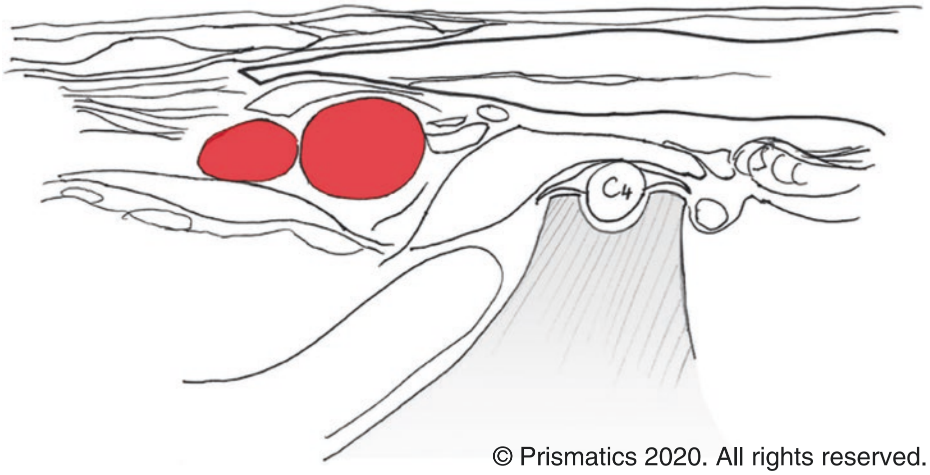
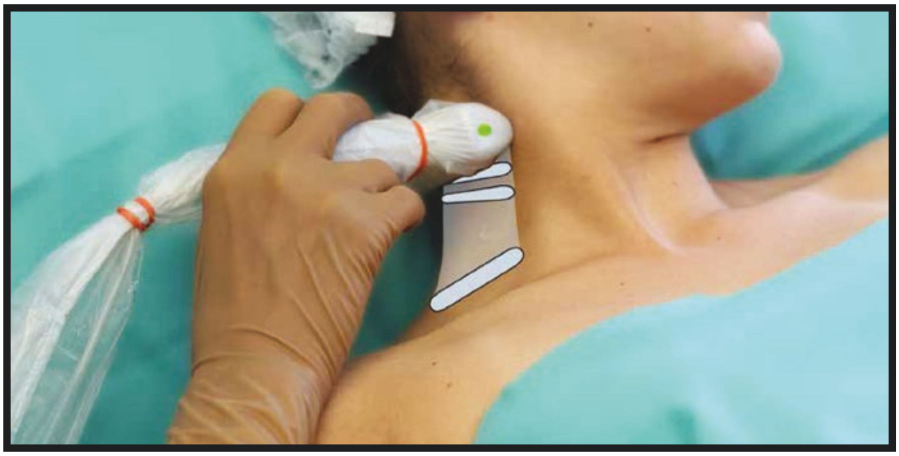
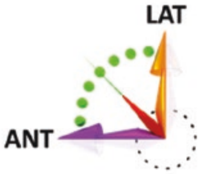
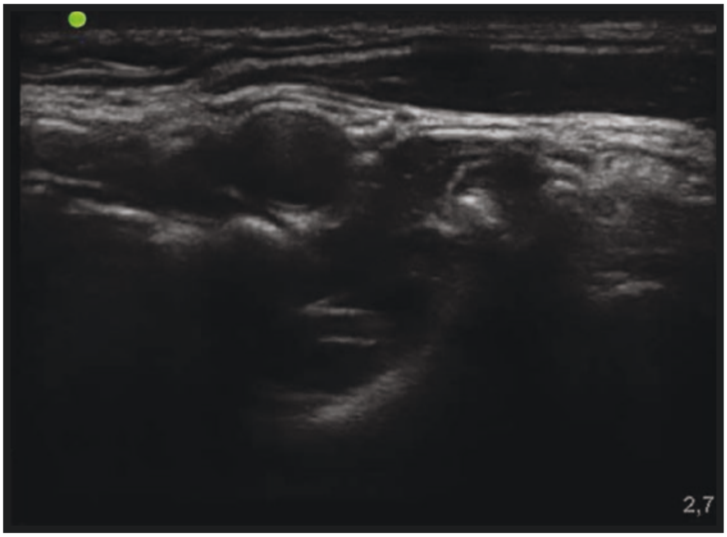


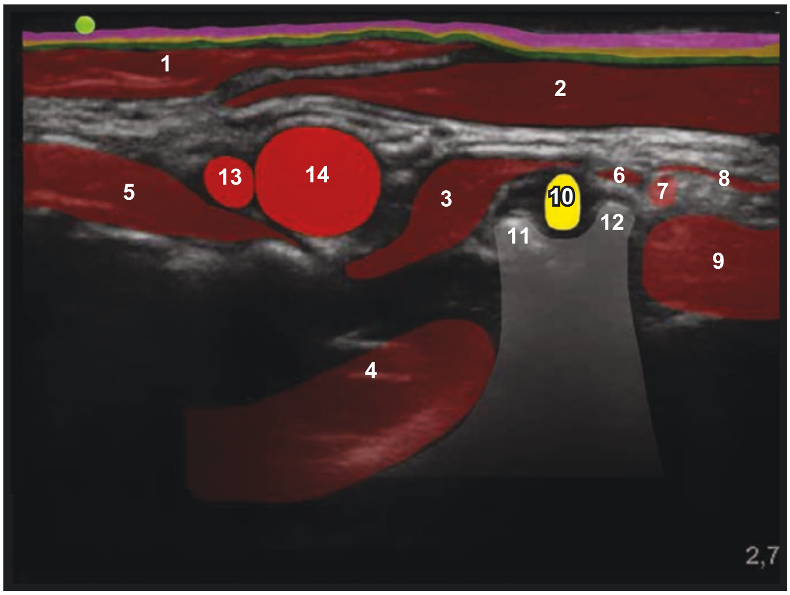
Figure BP8. Schematic view of ultrasound transversal at C4 level. Key landmarks: the volcano sign (grey) and carotid artery bifurcation (red).





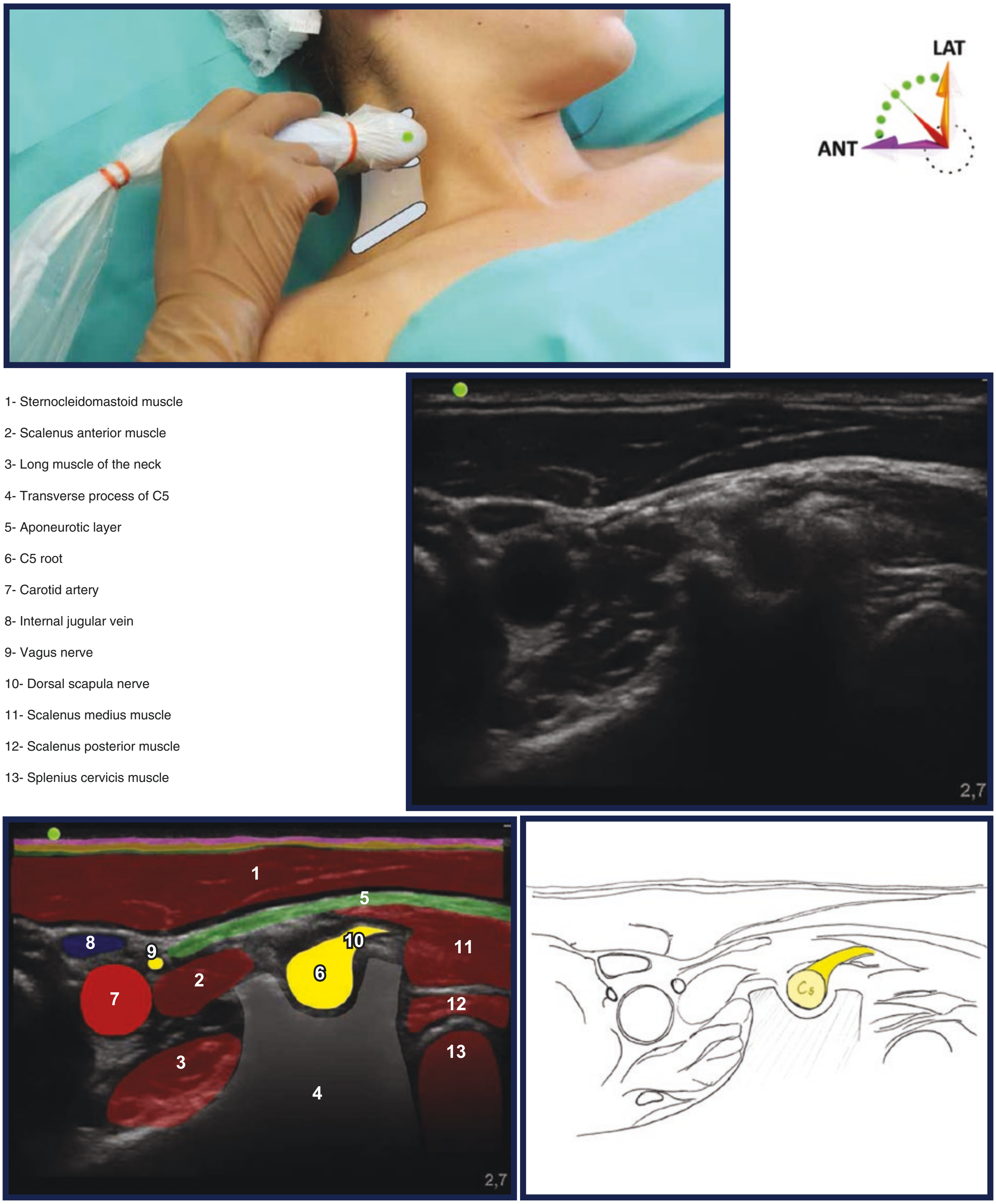
1- Platysma muscle
2- Sternocleidomastoid muscle
3- Superior muscle bundle of scalenus anterior muscle
4- Long muscle of the neck
5- Inferior pharyngeal muscle
6- Scalenus medius muscle’s tendinous insertion
7- Scalenus posterior muscle’s tendinous insertion





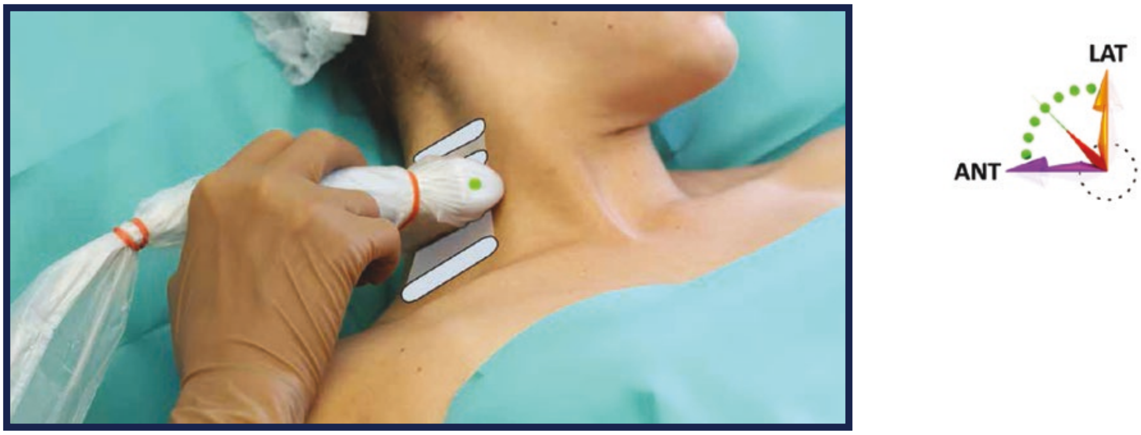
8- Inferior blade of levator scapulae muscle’s tendinous insertion
9- Splenius cervicis muscle
10- C4 root
11- Anterior tubercle of C4’s transverse process
12- Posterior tubercle of C4’s transverse process
13- External carotid artery
14- Internal carotid artery (the most anterior)

Figure BP9. Ultrasound views at C4 level.



1- Sternocleidomastoid muscle
2- Scalenus anterior muscle
3- Long muscle of the neck
4- Transverse process of C5
5- Aponeurotic layer
6- C5 root
7- Carotid artery
8- Internal jugular vein
9- Vagus nerve
10- Dorsal scapula nerve
11- Scalenus medius muscle
12- Scalenus posterior muscle
13- Splenius cervicis muscle

Figure BP10. Ultrasound views at C5 level. Key landmark: the toucan sign (yellow).



1- Sternocleidomastoid muscle

2- Scalenus anterior muscle

3- Scalenus medius muscle

4- Scalenus posterior muscle

5- C5 root

6- C6 root

7- Anterior tubercle of C6's transverse process

8- Posterior tubercle of C6's transverse process

9- Cervical posterior aponevrosis

10- Prevertebral layer of cervical fascia

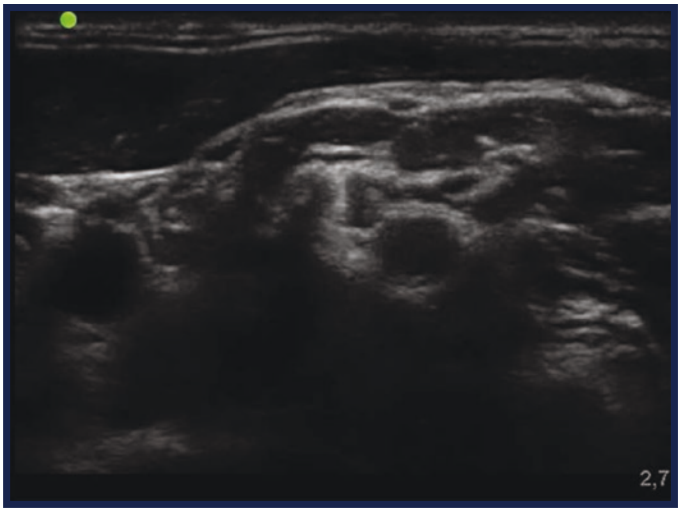
11- Carotid artery

12- External jugular vein

13- Long thoracic nerve

14- Dorsal scapular nerve

15- Phrenic nerve



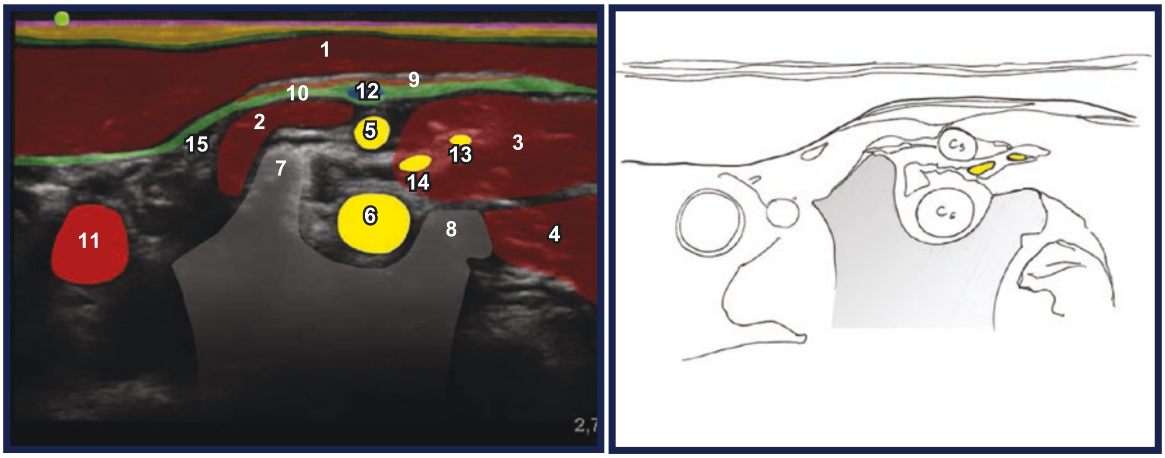


Figure BP11. Ultrasound views at C6 level. Key landmarks: anterior tubercle of the C6 transverse process (grey) and crossing of long thoracic and dorsal scapular nerves at the scalenus medius muscle.

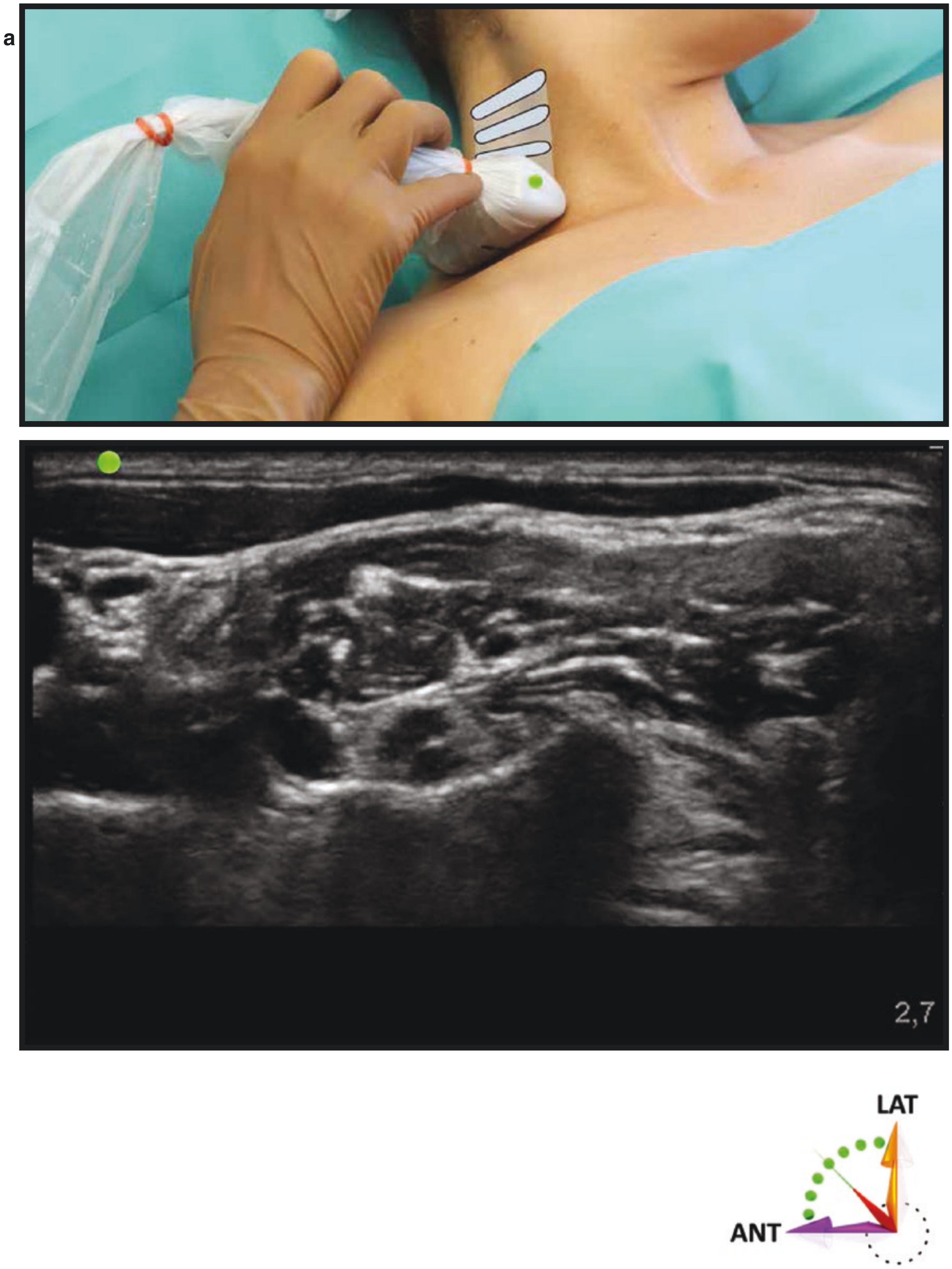
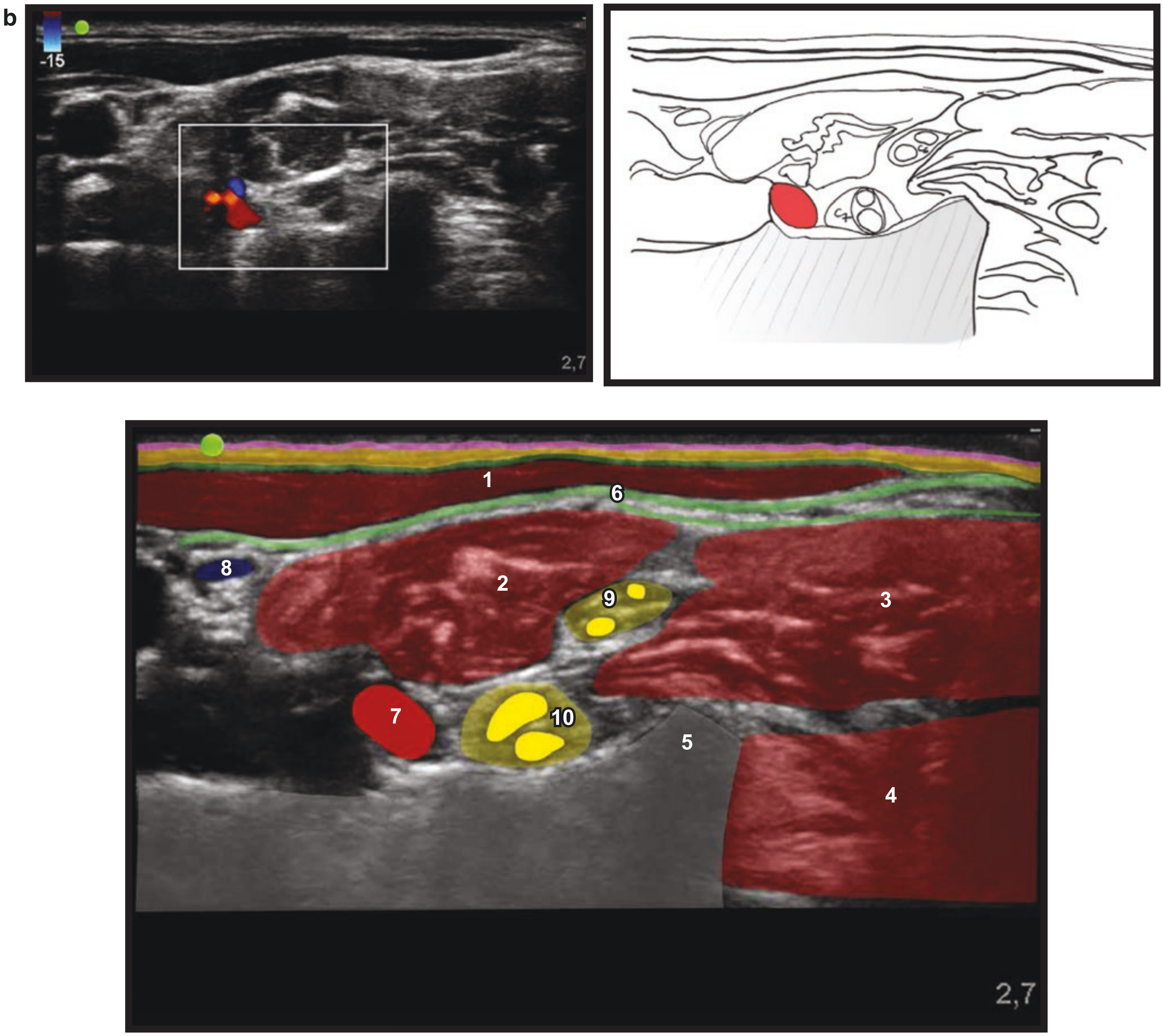


Figure BP12. (**a**) Echographic view. (**b**) Ultrasound transversal view at C7 level (Doppler mode). Key landmarks: lack of anterior tubercle highlighting the posterior tubercle (grey) and adjacent vertebral artery (red).



1- Sternocleidomastoid muscle

2- Scalenus anterior muscle

3- Scalenus medius muscle

4- Scalenus posterior muscle

5- Posterior tubercle of C7's transverse process

6- Prevertebral layer of cervical fascia

7- Vertebral artery

8- External jugular vein

9- Division of the brachial plexus' superior trunk (C5-C6) in anterior and posterior branches

10- Division of the brachial plexus' medial trunk (C7) in anterior and posterior branches

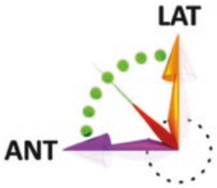


Figure BP13. Ultrasound views at C7 level.

Interventional Procedure

Neurostimulation of the Brachial Plexus

Neurostimulation of the brachial plexus is indicated in the management of refractory neuropathic pain in the upper limb. To determine the positioning of the stimulation electrode, it is important to translate the topography of neuropathic pain into root, truncated or fascicular territory. For scapular pain, identification of the entanglement of certain suprascapular, long thoracic, dorsal scapular neuropathies is essential in determining the insertion height of the probe.

The identification of cervical root structures and the recognition of certain collateral nerves of the plexus represent the basis of this technique.

Interscalenic Track

This route is indicated in neuropathic pain corresponding to the C5–C6 or, at times, the C7 branches.

In these frequently periscapular pains, the positioning of the electrode is relatively cranial, with a risk of puncture of the phrenic nerve (maximum at C5 level), which is immediately adjacent to the upper trunk.

It is important to search involvement of the collateral branches of the plexus in the patient's painful symptomatology (suprascapular nerve and/or dorsal scapular nerve and/or long thoracic).

The dorsal scapular nerve is a collateral branch of C5 emerging from the suprascapular part of the brachial plexus.

The long thoracic nerve is classically a motor nerve stemming from the anterior branches of several cervical roots, C5–C6–C7. It exits the brachial plexus through the scalene middle muscle.

The suprascapular nerve originates from the C5 root or the upper trunk, which it exits by crossing the deep face of the omohyoid muscle.

Not only must the collateral nerves useful for neurostimulation be identified, but the phrenic nerve and the vascular structures have to be avoided.

Installation

Patient in supine position, head in slight contralateral rotation to open a medium and low cervical space.

Equipment and Location

- Probe type: linear at high frequency
- Probe axis: transversal

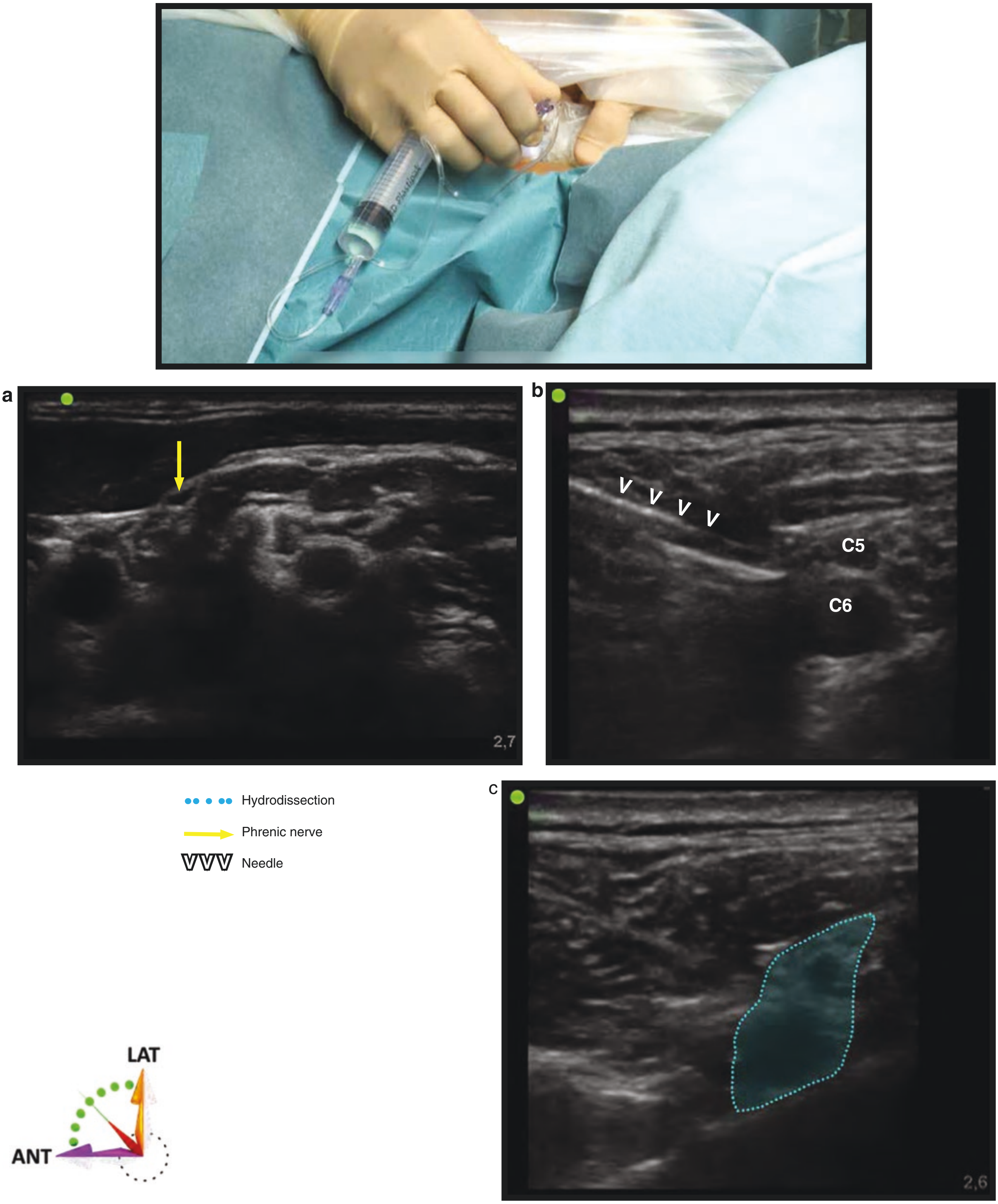

a
b
V V V V
C5
C6
2,7
c
2,6
Hydrodissection
Phrenic nerve
Needle
LAT
ANT

Figure BP14. C5–C6 brachial plexus neuromodulation. Anterior interscalenic approach. (**a**) Phrenic nerve identification. (**b**) Needle positioning (white arrows). (**c**) Lead implementation facilitated by hydrodissection.

Procedure

The incision will be located outside the manubrium of sternum, at the outer edge of the sternal head of the sternocleidomastoid muscle.

After careful ultrasound identification, target and best incidence identification are performed to exclude vascular risk and phrenic nerve puncture.

The probe outline is drawn with a dermographic pencil to guide the identification procedure during the strict asepsis process. When placing a definitive lead, it is also advisable to draw the location of the incision that will be used for proximal aponeurotic fixation of the stimulation lead. Anaesthesia will be light with the possibility of waking up to perform an intraoperative test. Local anaesthesia must remain superficial to avoid lexical blockage in case of deep subcutaneous diffusion.

A protective cover of the ultrasound probe is systematically used to implement strict surgical asepsis.

The percutaneous stimulation lead is placed in the ultrasound field (in plane), also assisted by hydrodissection.

It is carried out preferably with glucose 5% or physiological saline.

As the plexus approaches, it becomes imperative to facilitate identification of structures and reduce the risk of nerve puncture. Hydrodissection must be done with a visual control in real time. Any morphological modification of the lexical structure must stop the procedure, as it implies passage of the intraneural or intrafascicular barrier related to hydrodissection. On the other hand, lack of visualization of the product during injection or distension of adjacent structures indicates a probable vascular passage.

The correct positioning of the stimulation lead is validated by ultrasound visualization of at least two plots in immediate contact with the chosen structures.

It will also be validated by an intraoperative stimulation test, either sensory or motor, with low intensity (<0.5 V) and a pulse duration of less than 120 µs.

Once the positioning of the lead has been confirmed, the lead should be carefully secured to the skin for a temporary test device whilst a non-absorbable anchor should be used in the aponeurotic plane, when it is a definitive lead. Whilst the new injectable anchoring systems seem interesting, they are cumbersome.

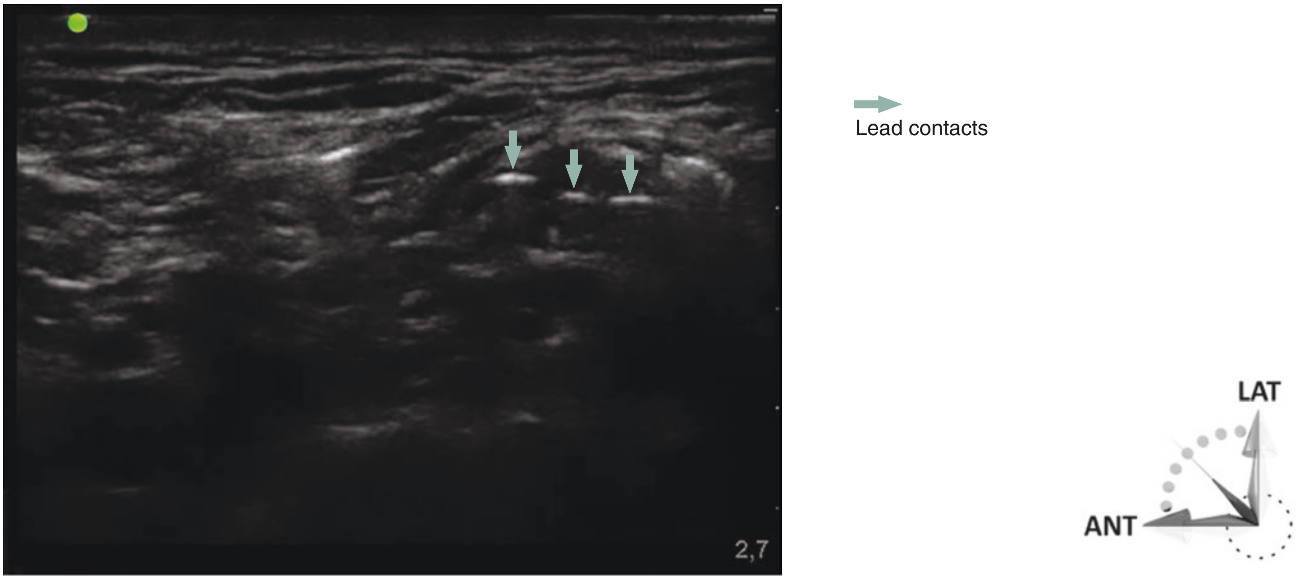


Figure BP15. C5–C6 brachial plexus neuromodulation. Anterior interscalenic approach.

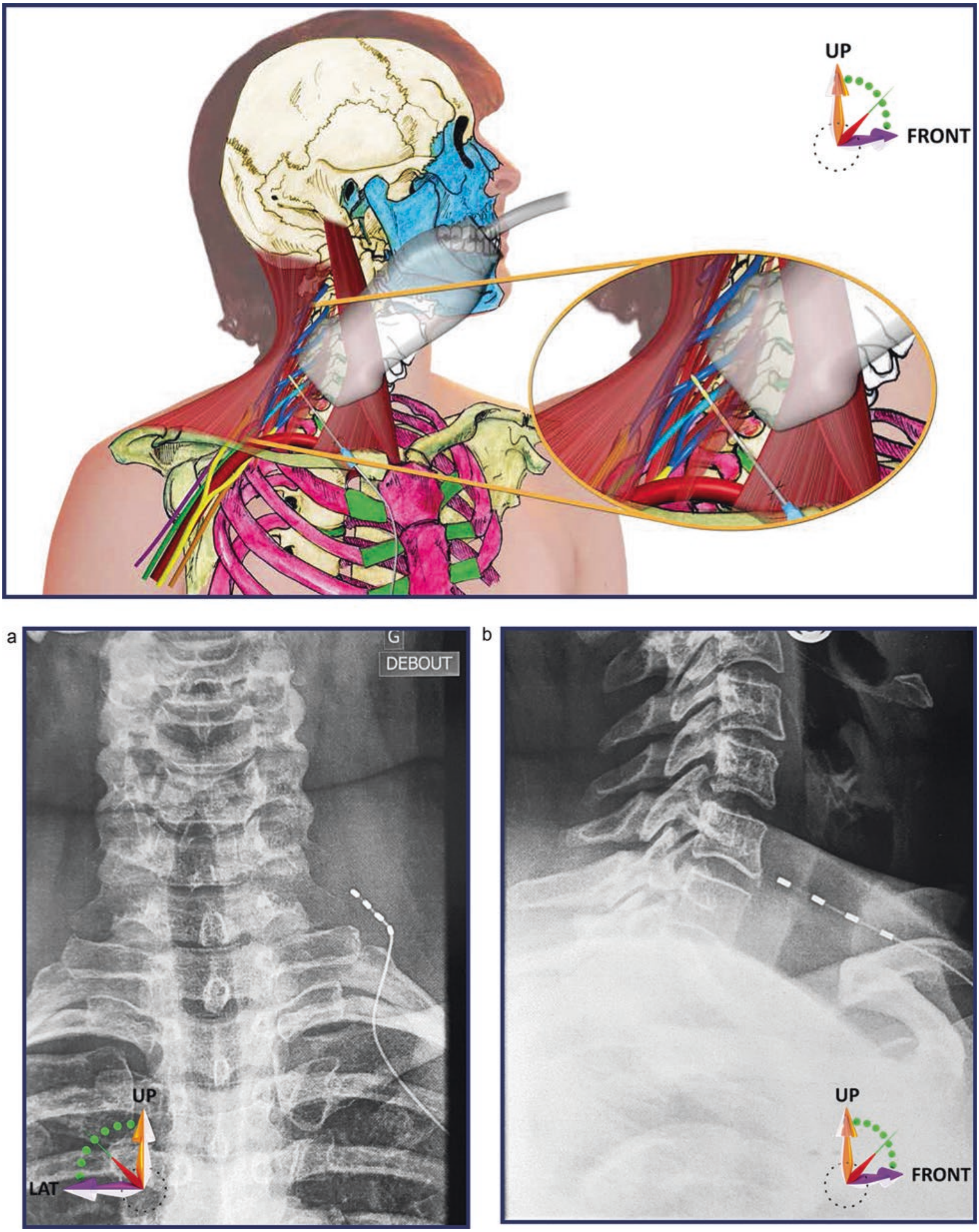

UP
FRONT
a
G
DEBOUT
UP
LAT
b
UP
FRONT

Figure BP16. Post-op X-ray showing C5–C6 lead position. Anterior interscalenic approach.

Supraclavicular Pathway

This pathway is indicated in cases of neuropathic pain in the upper limbs, which can be translated into root topographies at levels C6 to C7 or C8. For the latter, the choice of a supra- or infraclavicular approach will depend on the patient's anatomy.

It will be necessary to opt for a more caudal positioning of the lead than for neurostimulation of the brachial plexus by the interscalenic route.

The incision is much more lateral than in the previous technique. It is located at the supra-clavicular cavity, midway between the sternal head and the acromioclavicular joint, just behind and above the upper edge of the collarbone.

The risk of puncturing the phrenic nerve is much lower, as it is much more medial at this level. However, it is necessary to remain systematic in the process of structural vascular-nervous identification. Once the target is locked (e.g., C7), the rest of the procedure will be based on its continuous ultrasound monitoring.

It becomes important on this floor to visualize the ventral and dorsal divisions of the roots.

The other essential point is the search for vascular structures crossing the plexus at the supra-clavicular level, including the thyro-cervical trunk. It is therefore necessary to adapt the positioning of the probe in order to find the best angle between the target and the vessels.

Installation

Patient in supine position, head in slight contralateral rotation, in order to open the intermuscular channel between the sternocleidomastoid muscle, inside, and the trapezius muscle outside.

Equipment and Location

- Probe type: linear, high frequency
- Probe axis: transverse

Procedure

Once the anatomical landmarks have been identified, the procedure is identical to the interscalenic pathway, but centred on C7 .

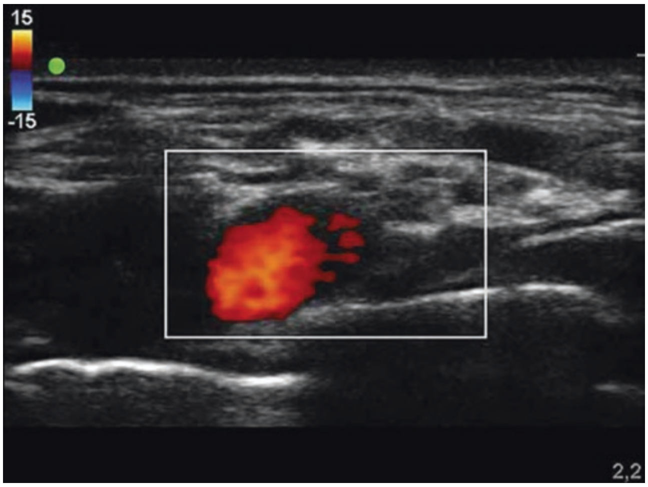


Figure BP17. Subclavian artery in Doppler mode.

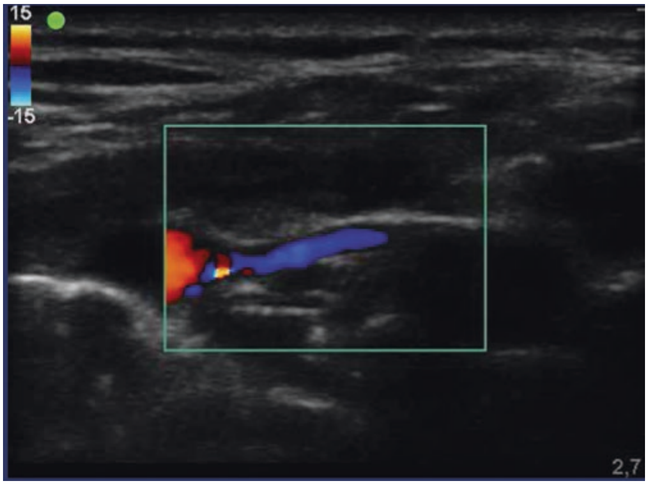
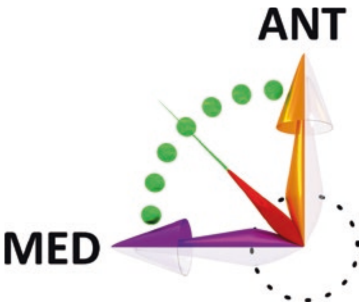
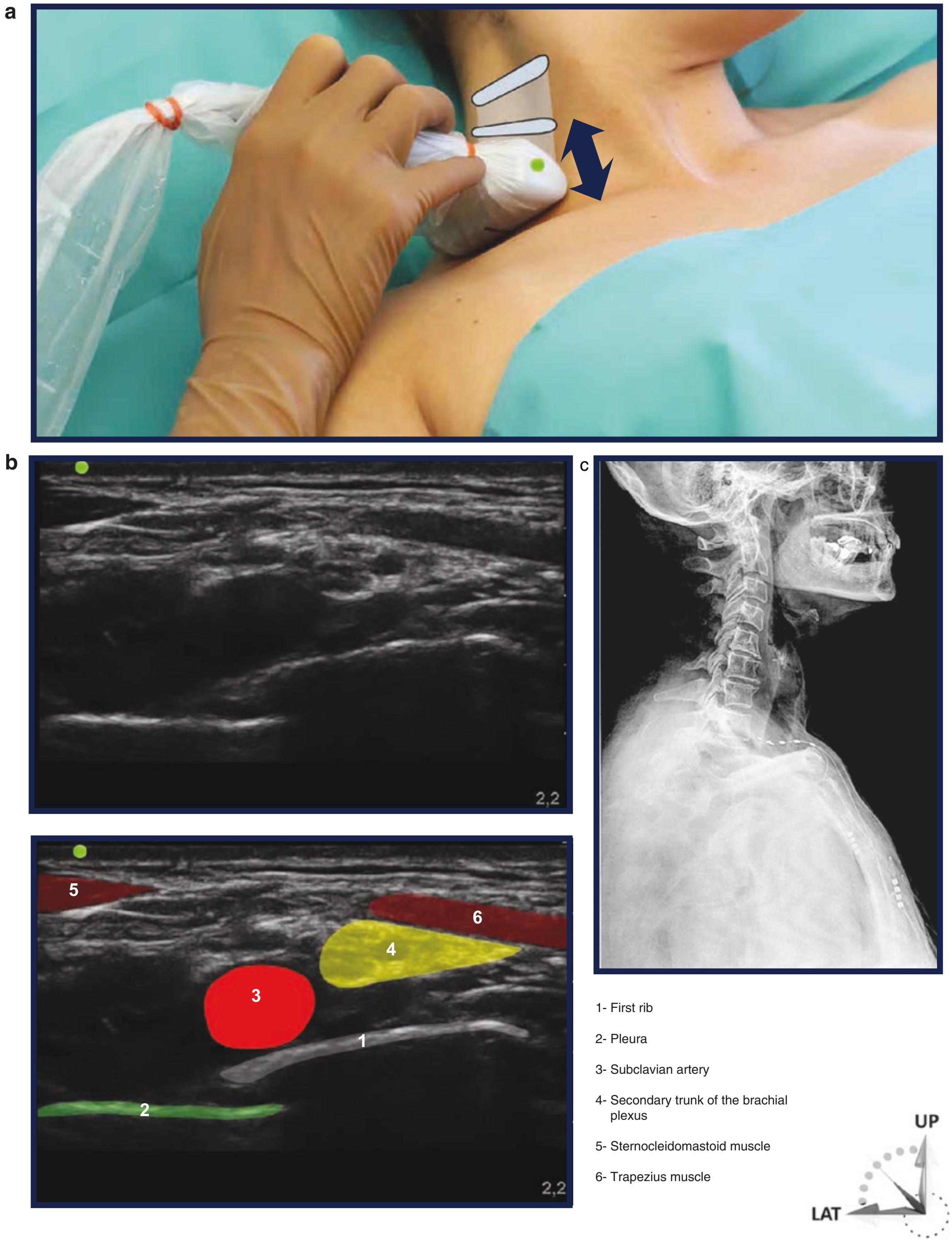


Figure BP18. Brachial plexus crossing of the dorsal scapular artery. Doppler mode required before any interventional procedure.





1- First rib

2- Pleura

3- Subclavian artery

4- Secondary trunk of the brachial plexus

5- Sternocleidomastoid muscle

6- Trapezius muscle

Figure BP19. C6–C7 brachial plexus neuromodulation. Supra-clavicular approach. (**a**) Ultrasound view. (**b**) Ultrasound views of a brachial plexus secondary trunk in the supra-clavicular region. (**c**) Brachial plexus neuromodulation. Post-op X-ray showing the lead position. Supra-clavicular approach. © Prismatics 2020.

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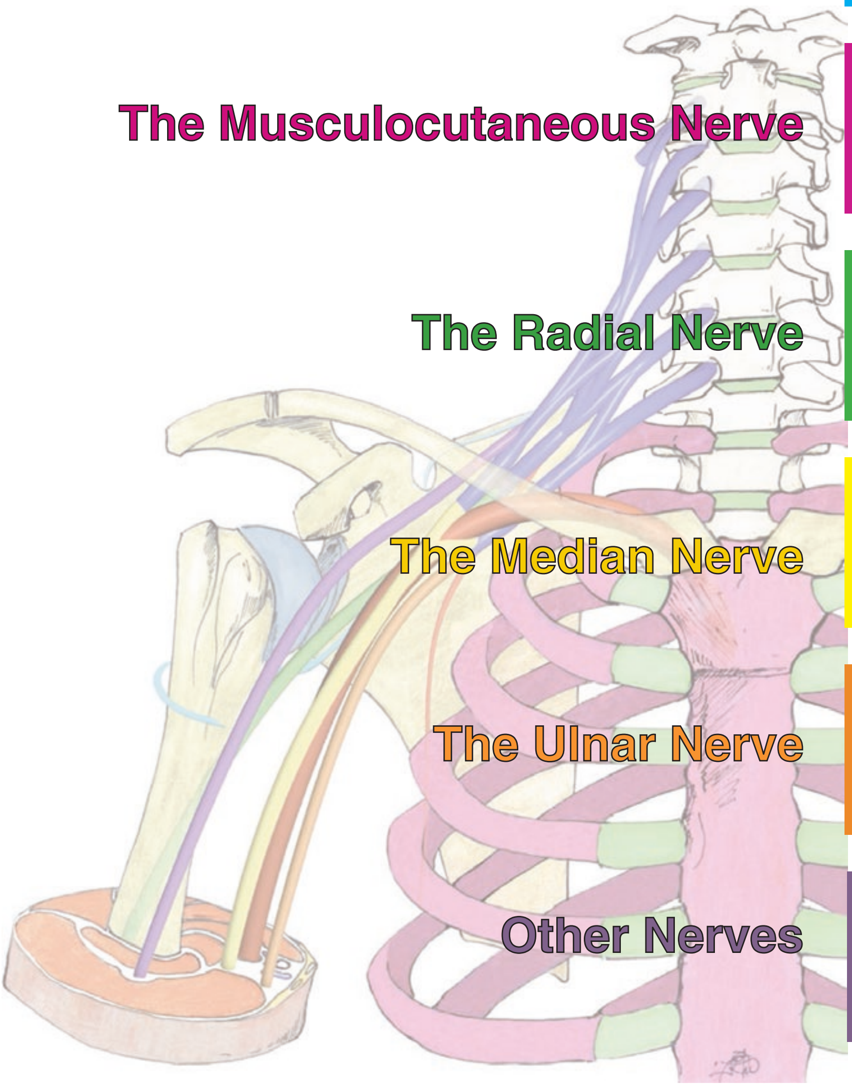
PERIPHERAL BRANCHES



The Axillary Nerve **Ax**

The Musculocutaneous Nerve **MC**

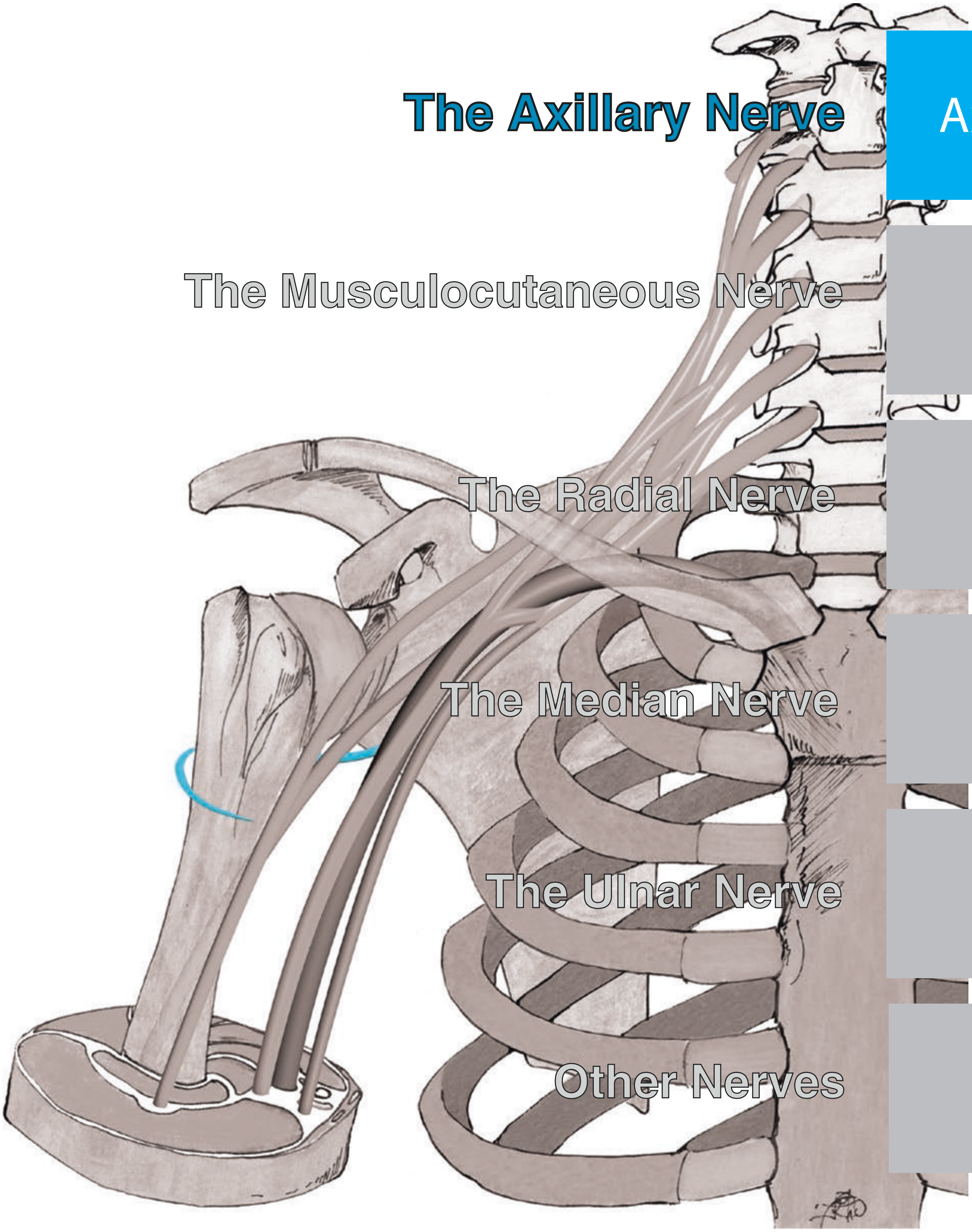
The Radial Nerve **R**

The Median Nerve **M**

The Ulnar Nerve **U**

Other Nerves **SSc TL**

The Axillary Nerve



The Musculocutaneous Nerve

The Radial Nerve

The Median Nerve

The Ulnar Nerve

Other Nerves

The Axillary Nerve

Morphological Data

The axillary nerve is a mixed nerve. It represents one of the two terminal branches of the posterior bundle of the brachial plexus and is responsible for the innervation of the scapular area and the shoulder stump.

Origin

It is made of nerve fibres coming from the posterior divisions of the upper trunk of the plexus, itself coming from the upper trunks of C5 and C6 (Figures Ax1 and Ax2).

Path

The axillary nerve originates from the anterior face of the subscapularis muscle, from behind the axillary artery, leaving the radial nerve in a medial position (Figure Ax3). It goes down and laterally and then crosses the lateral axillary space below the capsule of the glenohumeral joint. It then goes around the hind face of the surgical neck of the humerus in a bone groove against the deep face of the deltoid muscle and then expands from it (Figures Ax4 and Ax5).

Neurovascular Relations

In its posterior part, slightly before penetrating the lateral axillary space, the axillary nerve faces the posterior circumflex artery of the humerus below and remotely (Figure Ax4). It joins this artery at the inferior border of the subscapularis muscle until the posterior face of the humerus, whilst it goes around the surgical neck. In the lateral axillary space, the posterior humeral circumflex artery comes across the axillary nerve from behind (Figure Ax6) and goes up again towards the proximal extremity of the humerus, at the deep face of the deltoid muscle (Figure Ax4).

Collateral Branches

The axillary nerve innervates the following branches in succession (Figures Ax2, Ax4, Ax5 and Ax6):

- Branches for the glenohumeral joint, from its anterior and posterior parts.
- Motor branches for the lower part of the subscapularis muscle, without taking charge of its main motor innervation which depends on the upper and lower subscapular nerves, which are direct collateral branches of the brachial plexus.
- The teres minor nerve: It originates in the lateral axillary space and goes around the inferior edge of the muscle before coming in contact with and going through it from its posterior face.
- Superior lateral cutaneous nerve of the arm: After finding its origin in the lateral axillary space, it goes around the deltoid muscle from its middle part and then runs behind it. It then comes across the aponeurosis of the deltoid muscle and distributes its branches to the adjacent skin. It takes charge of the sensitive function of the nerve (Figures Ax5 and Ax6).

Terminal Branches

The terminal branches of the axillary nerve are constituted by several motor branches for the deep face of the deltoid muscle (Figures Ax7, Ax8, Ax9 and Ax10).

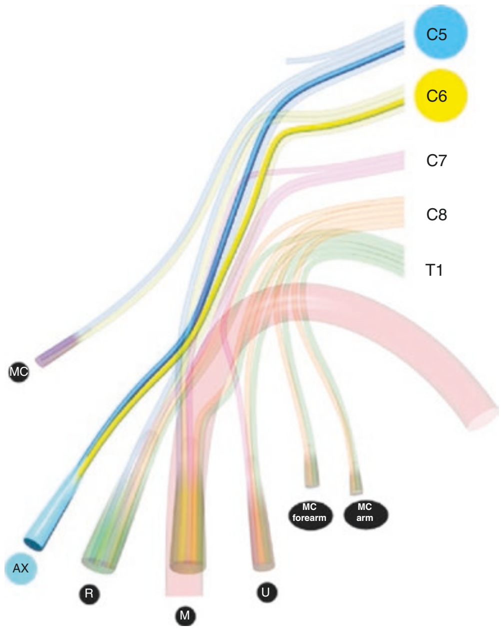


Figure Ax1. Origin of the axillary nerve.

Electronic Supplementary Material The online version of this chapter (https://doi.org/10.1007/978-3-030-49179-6_5) contains supplementary material, which is available to authorized users.

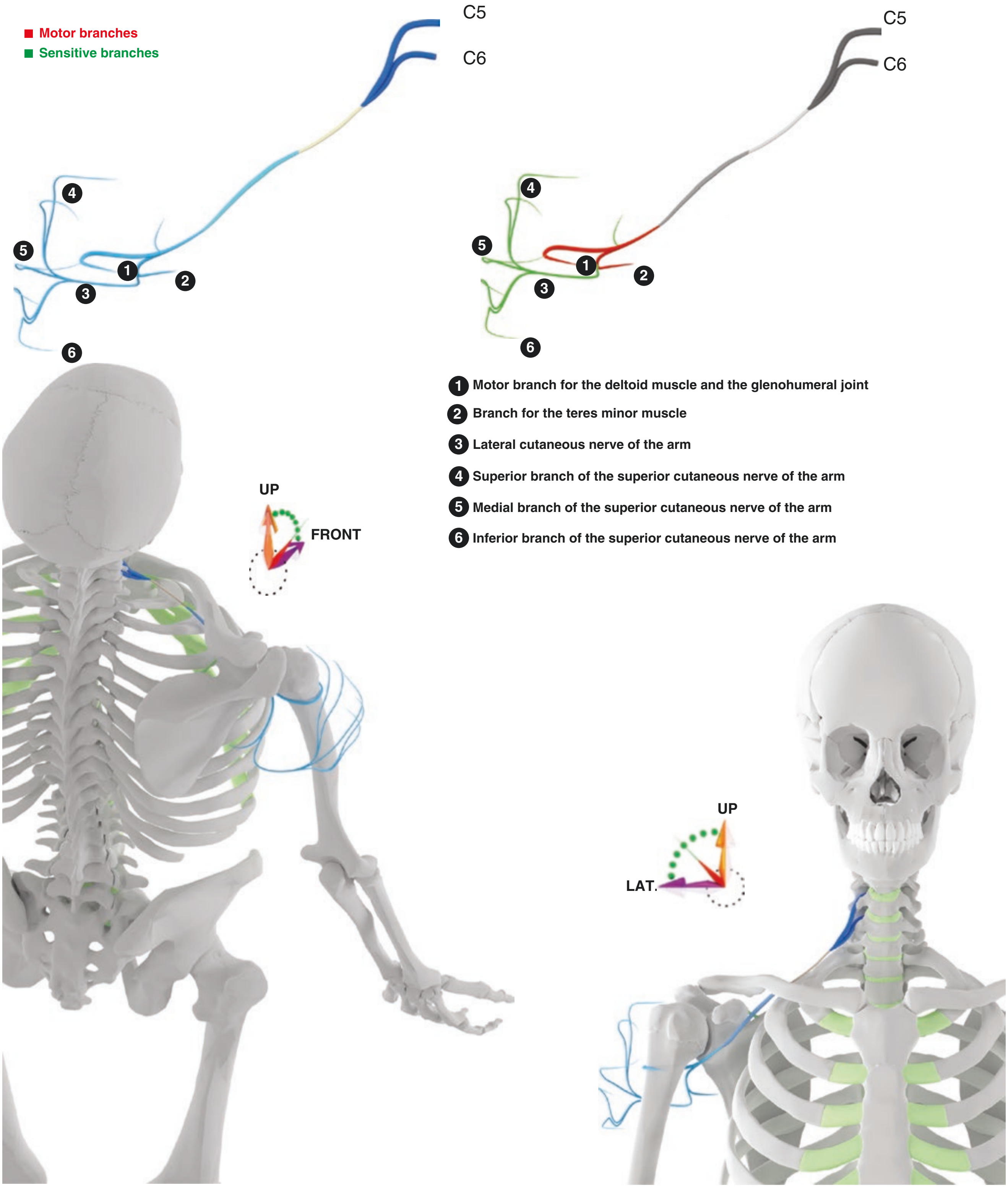

🟥 Motor branches
🟩 Sensitive branches
C5
C6
C5
C6
4
5
1
2
3
6
4
5
1
2
3
6
① Motor branch for the deltoid muscle and the glenohumeral joint
② Branch for the teres minor muscle
③ Lateral cutaneous nerve of the arm
④ Superior branch of the superior cutaneous nerve of the arm
⑤ Medial branch of the superior cutaneous nerve of the arm
⑥ Inferior branch of the superior cutaneous nerve of the arm
UP
FRONT
UP
LAT.

Figure Ax2. Topographical distribution of the axillary nerve and its relations with bones.

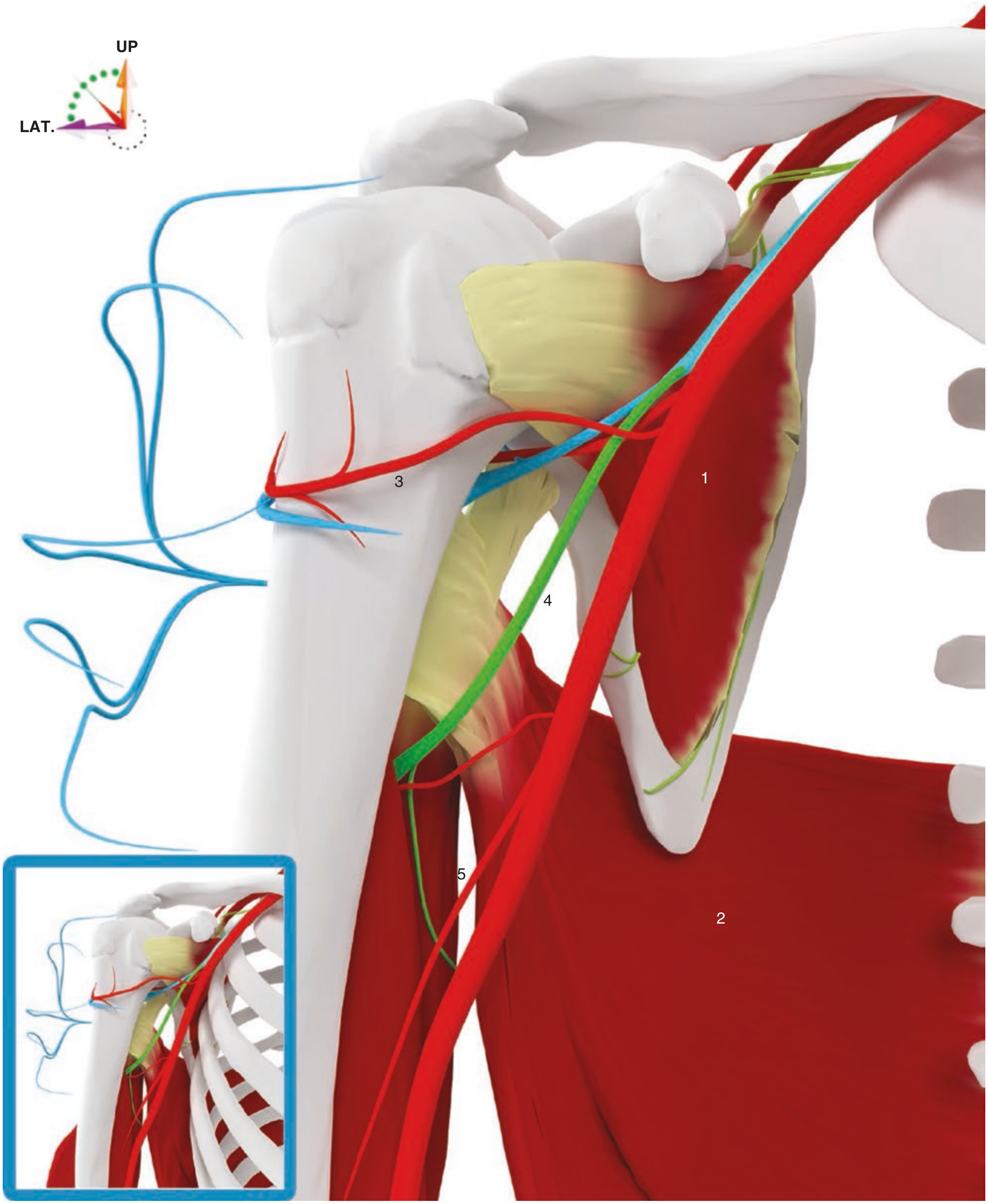


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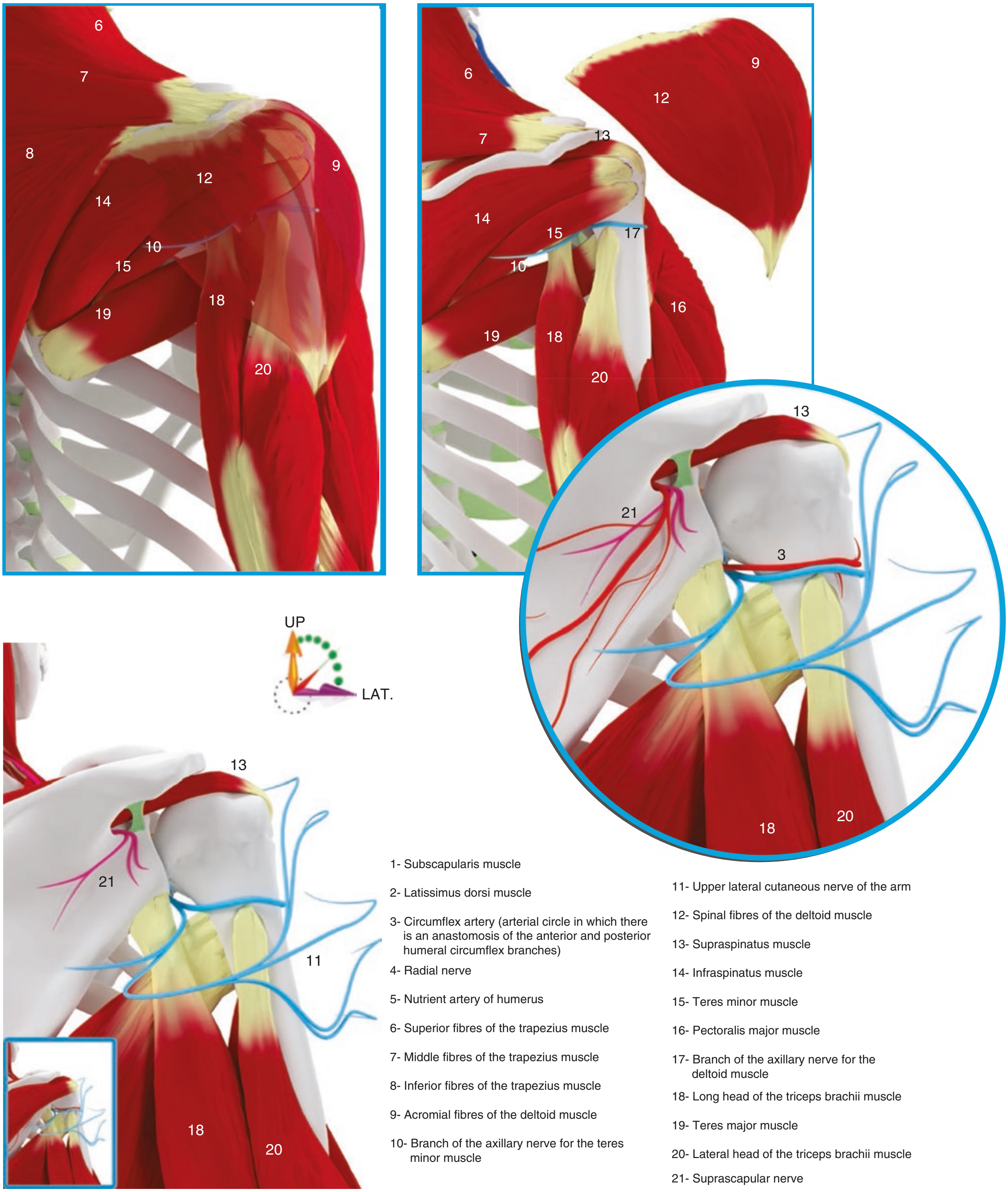
Figure Ax3. Path of the axillary nerve and anterior view of its terminal branches.



1- Subscapularis muscle

2- Latissimus dorsi muscle

3- Circumflex artery (arterial circle in which there is an anastomosis of the anterior and posterior humeral circumflex branches)

4- Radial nerve

5- Nutrient artery of humerus

6- Superior fibres of the trapezius muscle

7- Middle fibres of the trapezius muscle

8- Inferior fibres of the trapezius muscle

9- Acromial fibres of the deltoid muscle

10- Branch of the axillary nerve for the teres minor muscle

11- Upper lateral cutaneous nerve of the arm

12- Spinal fibres of the deltoid muscle

13- Supraspinatus muscle

14- Infraspinatus muscle

15- Teres minor muscle

16- Pectoralis major muscle

17- Branch of the axillary nerve for the deltoid muscle

18- Long head of the triceps brachii muscle

19- Teres major muscle

20- Lateral head of the triceps brachii muscle

21- Suprascapular nerve

Figure Ax4. Posterior view of the axillary spaces showing the path of the axillary nerve (from superficial to deep).

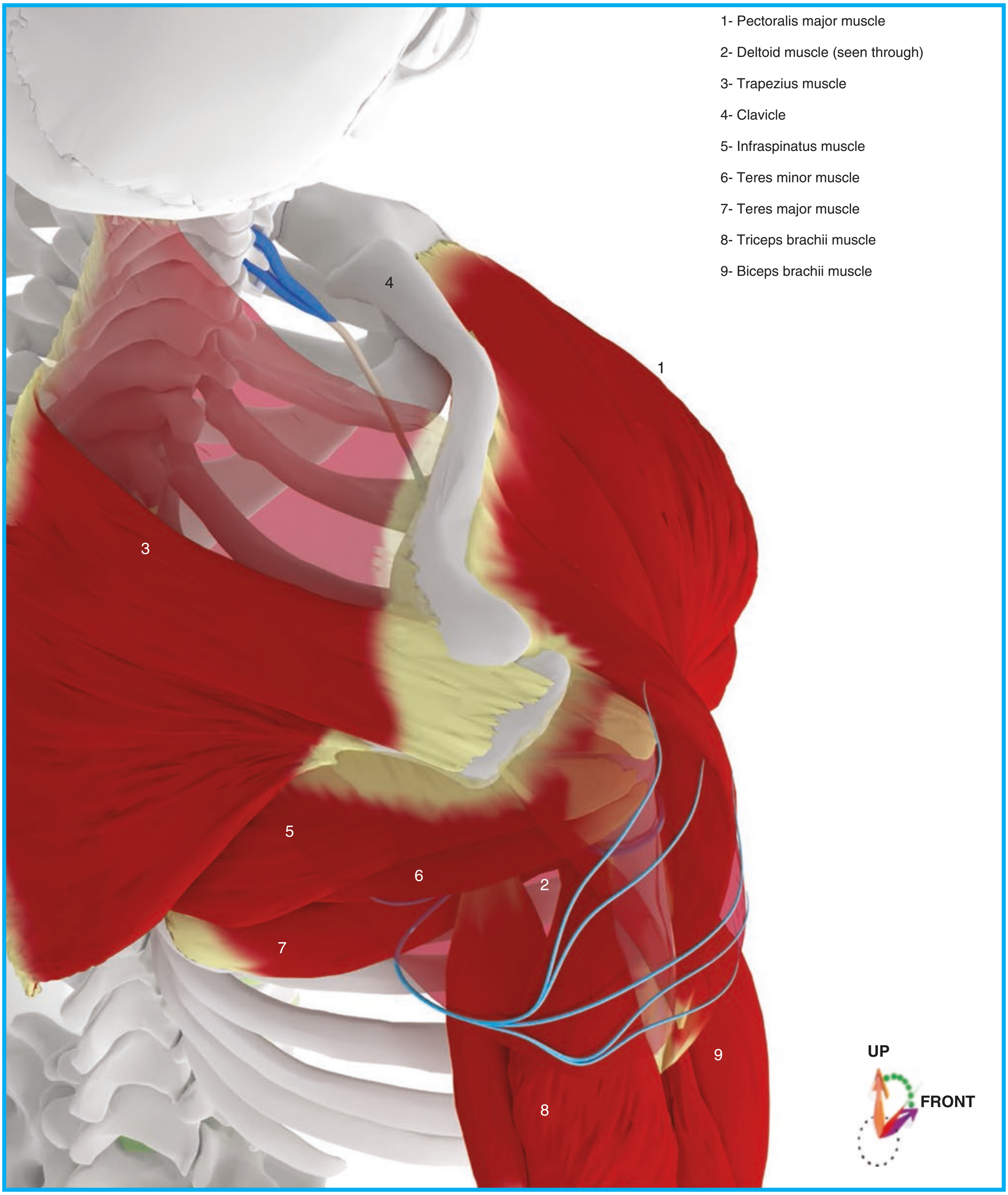
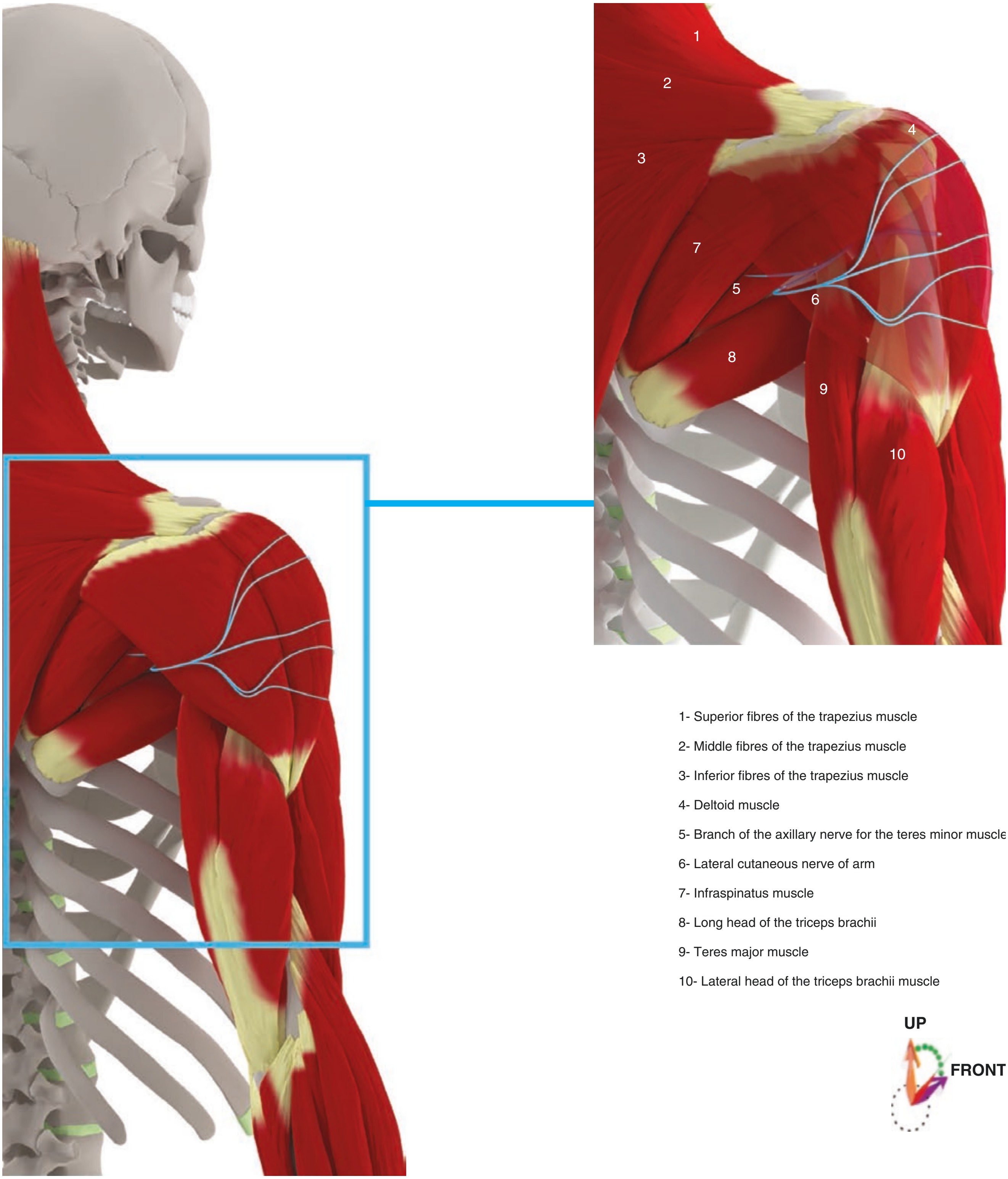

1- Pectoralis major muscle
2- Deltoid muscle (seen through)
3- Trapezius muscle
4- Clavicle
5- Infraspinatus muscle
6- Teres minor muscle
7- Teres major muscle
8- Triceps brachii muscle
9- Biceps brachii muscle
4
1
3
5
6
2
7
9
8
UP
FRONT

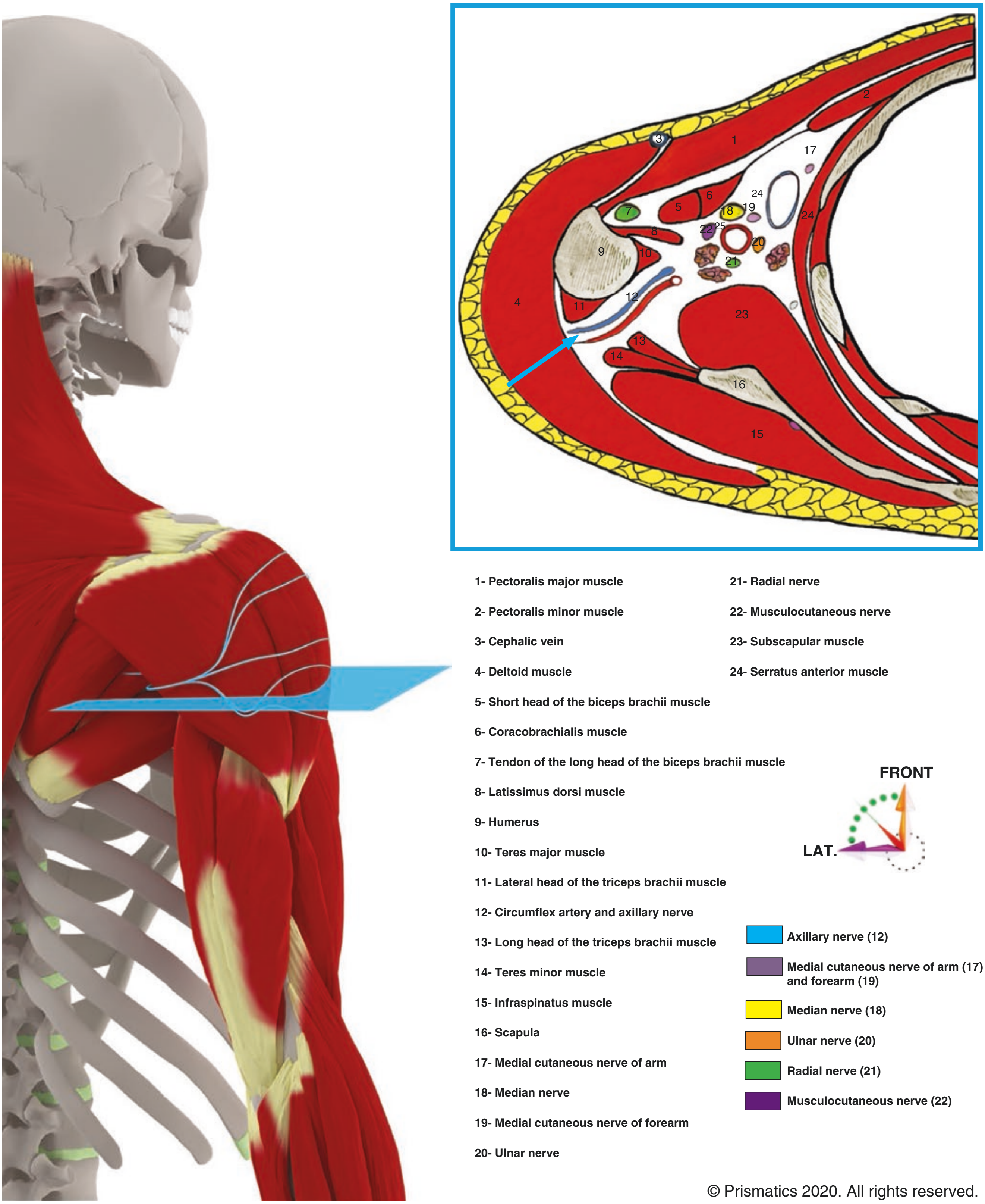
Figure Ax5. View from above of the lateral cutaneous nerve at the shoulder in contact with the deltoid muscle.



1- Superior fibres of the trapezius muscle
2- Middle fibres of the trapezius muscle
3- Inferior fibres of the trapezius muscle
4- Deltoid muscle
5- Branch of the axillary nerve for the teres minor muscle
6- Lateral cutaneous nerve of arm
7- Infraspinatus muscle
8- Long head of the triceps brachii
9- Teres major muscle
10- Lateral head of the triceps brachii muscle

Figure Ax6. Sensitive branches of the axillary nerve in the shoulder (posterior view).

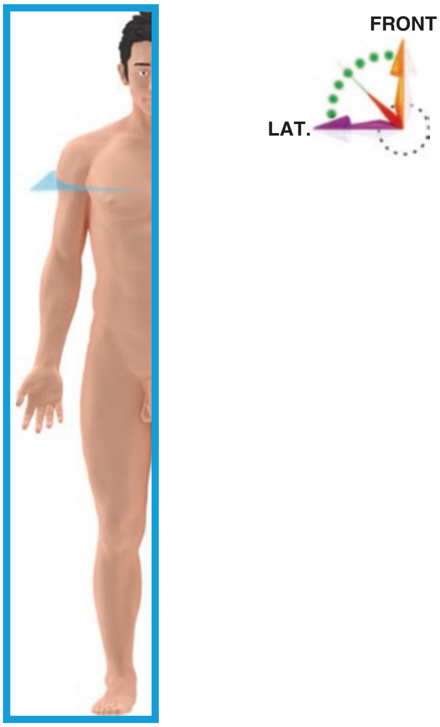
The Axillary Nerve

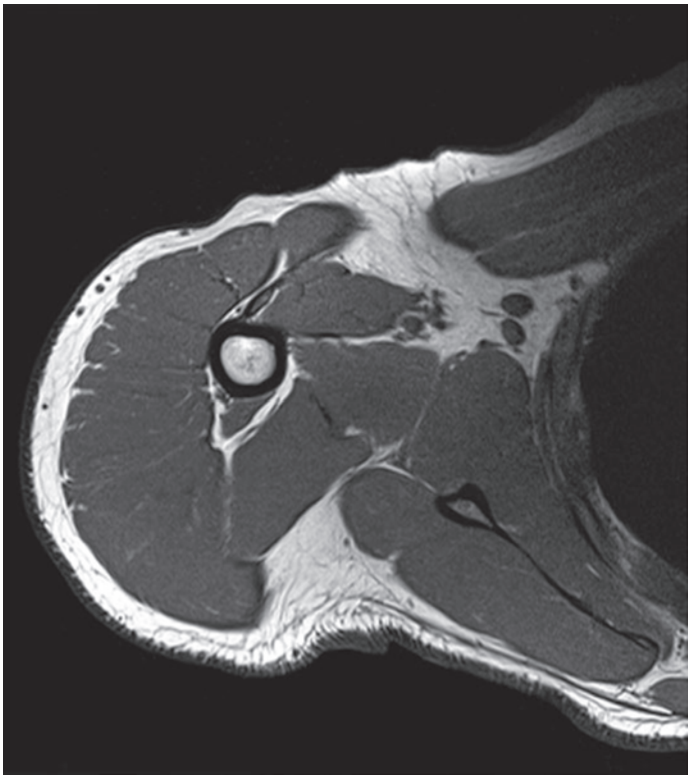


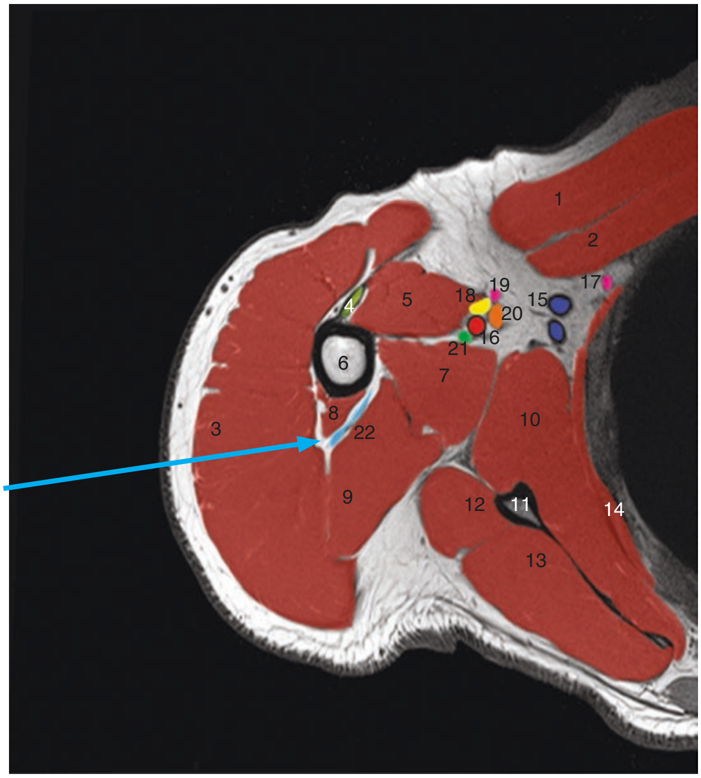
1- Pectoralis major muscle
2- Pectoralis minor muscle
3- Cephalic vein
4- Deltoid muscle
5- Short head of the biceps brachii muscle
6- Coracobrachialis muscle
7- Tendon of the long head of the biceps brachii muscle
8- Latissimus dorsi muscle
9- Humerus
10- Teres major muscle
11- Lateral head of the triceps brachii muscle
12- Circumflex artery and axillary nerve
13- Long head of the triceps brachii muscle
14- Teres minor muscle
15- Infraspinatus muscle
16- Scapula
17- Medial cutaneous nerve of arm
18- Median nerve
19- Medial cutaneous nerve of forearm
20- Ulnar nerve
21- Radial nerve
22- Musculocutaneous nerve
23- Subscapular muscle
24- Serratus anterior muscle

🟦 Axillary nerve (12)
🟪 Medial cutaneous nerve of arm (17) and forearm (19)
🟨 Median nerve (18)
🟧 Ulnar nerve (20)
🟩 Radial nerve (21)
🟪 Musculocutaneous nerve (22)

Figure Ax7. Relations of the axillary nerve in the shoulder in axial view.







1- Pectoralis major muscle

2- Pectoralis minor muscle

3- Deltoid muscle

4- Long head of the biceps brachii muscle

5- Latissimus dorsi muscle

6- Humerus

7- Teres major muscle

8- Lateral head of the triceps brachii muscle

9- Medial head of the triceps brachii muscle

10- Subscapularis muscle

11- Scapula

12- Teres minor muscle

13- Infraspinatus muscle

14- Serratus anterior

15- Brachial vein

16- Brachial artery

17- Medial cutaneous nerve of arm

18- Median nerve

19- Medial cutaneous nerve of forearm

20- Ulnar nerve

21- Radial nerve

22- Axillary nerve

Figure Ax8. MRI scans and axillary nerve in the shoulder.

The Axillary Nerve

Motor Function

The axillary nerve allows abduction and lateral rotation of the arm by innervation of the deltoid muscle (Figures Ax9 and Ax10).

Sensitive Function

The sensitive innervation territory of the axillary nerve corresponds to the shoulder stump (Figure Ax10).

Anastomoses

The axillary nerve frequently makes anastomoses with:

- The radial nerve by way of the lateral cutaneous nerve of the arm (a collateral branch of the axillary nerve) to join the posterior cutaneous nerve of the arm
- The medial cutaneous nerve of the arm, which is a terminal branch of the medial cord of the brachial plexus

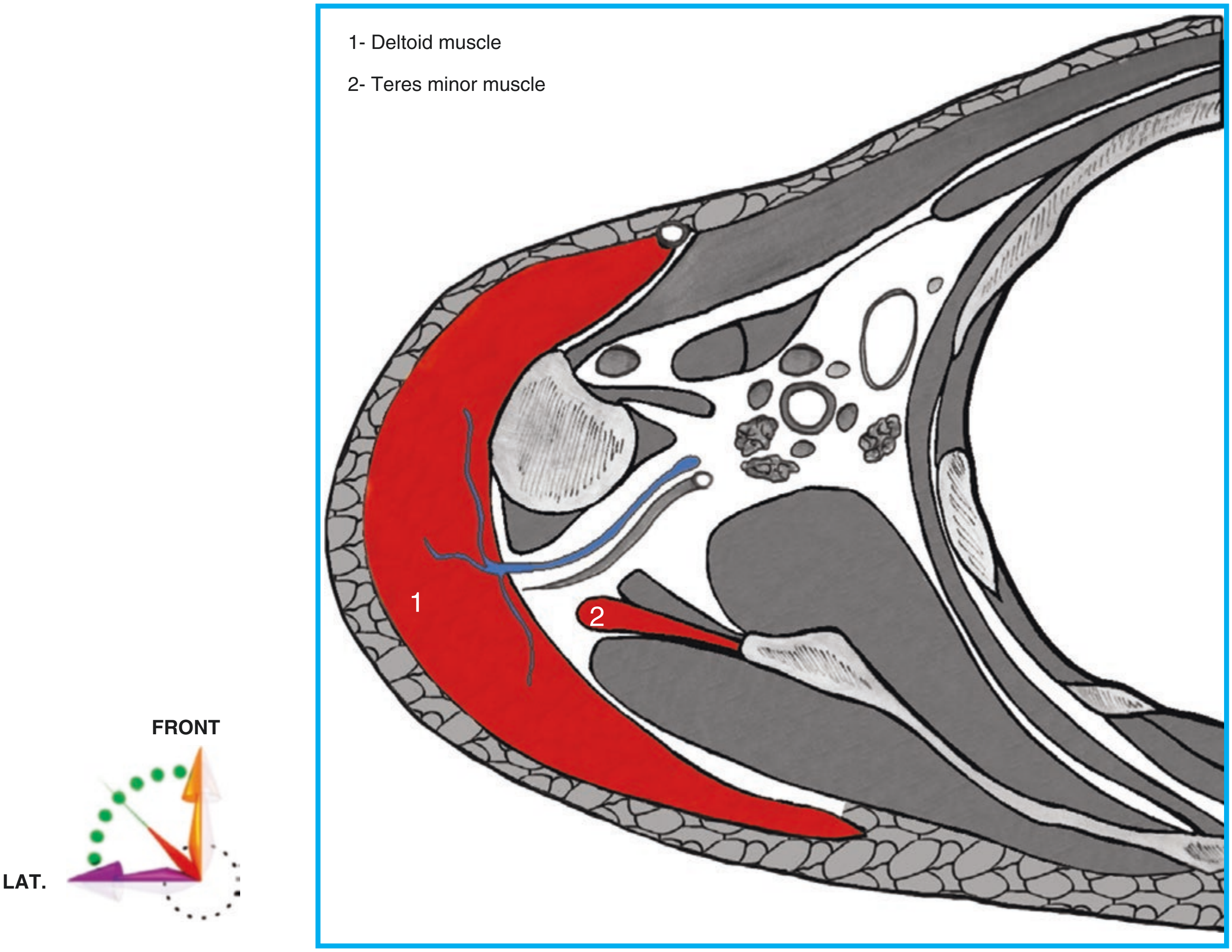


Figure Ax9. Motor innervation of the axillary nerve (axial view).

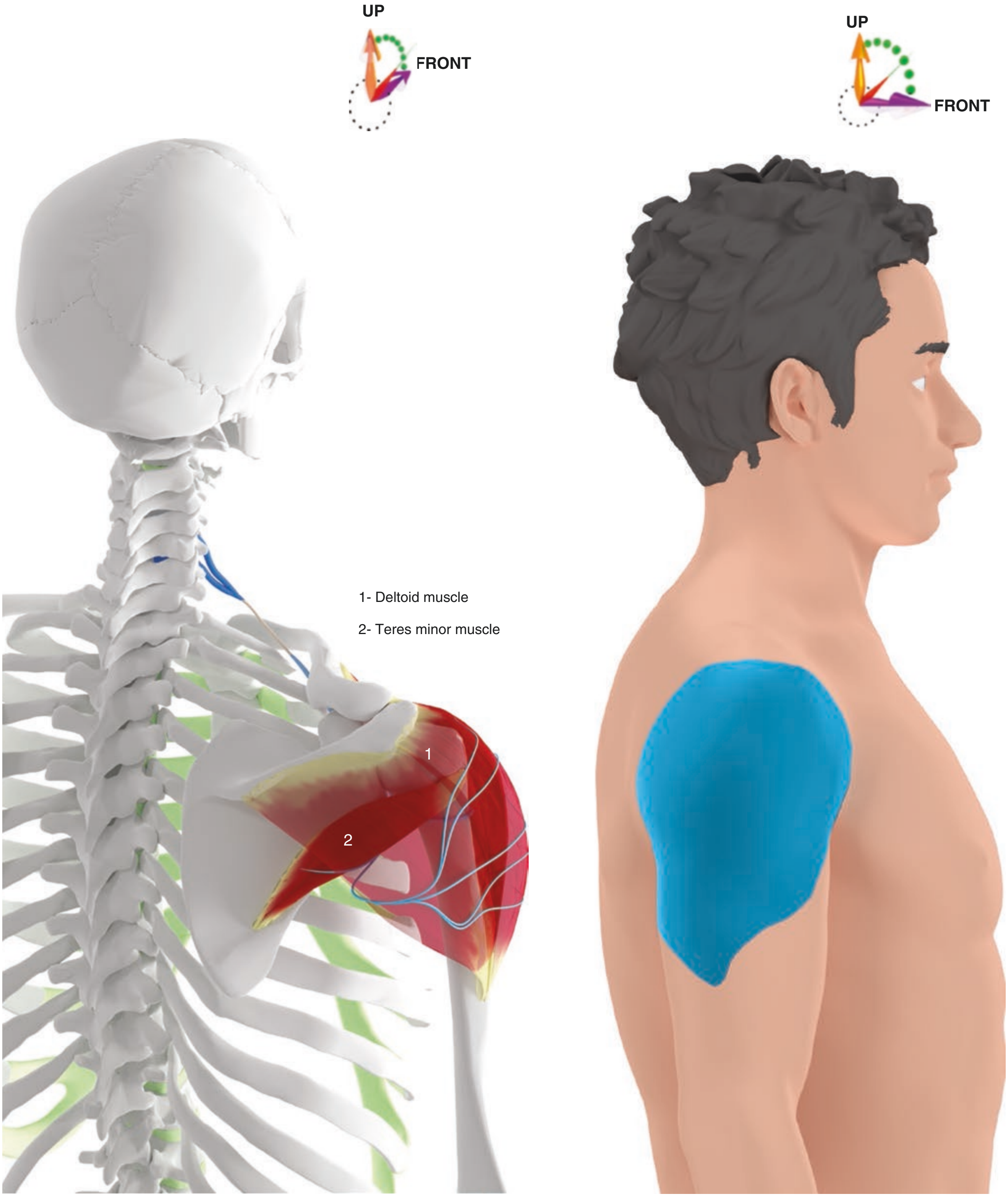

UP
FRONT
1- Deltoid muscle
2- Teres minor muscle
1
2
UP
FRONT

Figure Ax10. Motor and sensitive innervation of the axillary nerve.

Pathology

The axillary nerve can be damaged when it crosses the lateral axillary space (formerly known as the quadrilateral space of Velpeau). This space is laterally limited by the humerus, medially by the long head of the triceps brachialis, above it by the teres minor muscle and below it by the teres major muscle (Figure Ax11).

Aetiology

- Traction: This is the most frequent mechanism of injury, generally during an anterior inferior scapulohumeral dislocation. A stretching of the arm in abduction also causes traction on the axillary nerve, which may not be isolated. A fracture at the level of the superior extremity of the humerus can, if proximal, affect the axillary nerve along with the radial nerve, or the musculocutaneous and suprascapular nerves. In most cases, obstetric lesions affect the brachial plexus, not its peripheral terminal branches.
- Section: An isolated section of the axillary nerve can occur in posterior injury in the lateral axillary space.
- Compression: The use of traditional "crutches" (with subaxillary support) can compress the axillary nerve in the lateral axillary space. This can be avoided by the use of elbow crutches. Chronic compressions, encountered mostly in people who do large amounts of sport activities, are caused by a muscular compression by repeated movements of abduction and lateral rotation of the arm. It is then considered as a real entrapment neuropathy.

If no mechanical or traumatic cause can be found, it is important not to overlook a nerve compression by a cyst or any other swelling. An MRI examination of the axillary spaces is highly recommended.

Clinical Significance

- Sensitive signs: In the event of a chronic entrapment neuropathy, pain in the axillary nerve area is sporadic, with a definite neuropathic character consisting of intense pain with a burn-type feeling, more intense during night-time and on which traditional analgesics have no effect.
- Aforementioned anastomoses may allow for partial sensitive substitution in the case of a damaged axillary nerve. Pain can become more intense during palpation in the area of the lateral axillary space under the teres minor muscle on the posterior face of the shoulder.
- Motor signs: The motor innervation of the deltoid muscle is exclusively dependant on the axillary nerve; an injury of this nerve will cause an amyotrophy in the shoulder. A detailed examination of the shoulder and the whole upper limb is compulsory. Indeed, the axillary nerve is rarely the only thing damaged in such cases. A neurological and functional examination of the whole limb helps to find injury in other branches of the brachial plexus (generally the radial or suprascapular nerves).

Clinical Forms

A fracture at the superior extremity of the humerus, at the level of its surgical neck, can cause an injury of the axillary nerve and in turn a traction of the radial nerve at the level of the radial nerve's groove.

Explorations

- Shoulder radiography

  These can be executed in a front view, in a neutral position, in a position of medial and lateral rotation and in the Y view. Radiographies allow the detection of indirect signs of a rotator cuff-related pathology.
- Electromyography

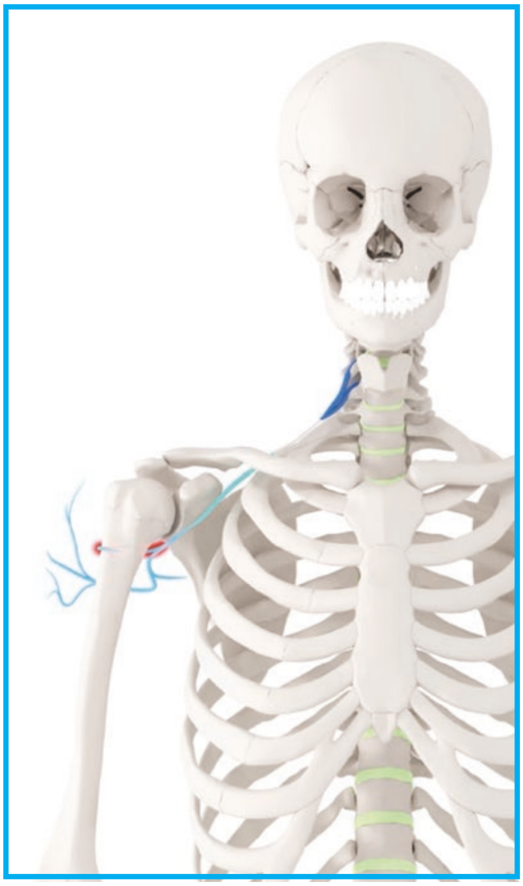
  Even though its execution is rather difficult, electromyography helps objectify an electrophysiological injury of the axillary nerve, isolated or not.
- Imaging of the soft parts of the shoulder

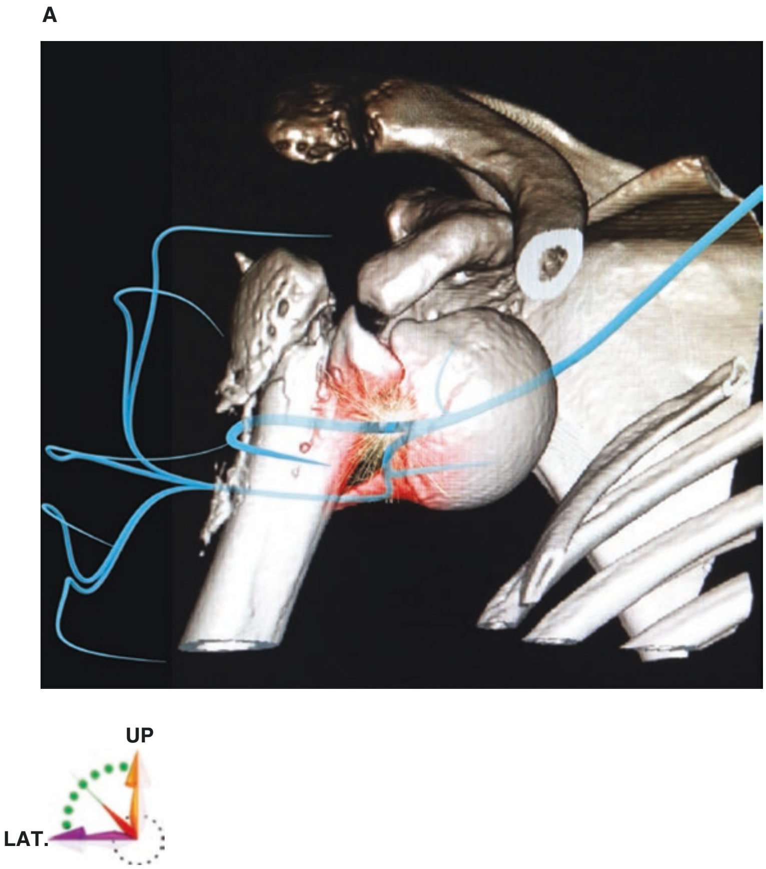
  An MRI of the armpit area is the best option. Further examination with an arthrogram can also be very informative.

Treatment

In proven cases of entrapment neuropathy, the first treatment consists in putting the glenohumeral joint to rest. An infiltration of corticosteroids in the lateral axillary space allows for temporary relief of pain, especially in the case of pathologies associated with the rotator cuffs.

If conservative treatment fails and no orthopaedic cause can be found, a surgical treatment option is decompression. This treatment is only prescribed after 3 months without benefit from rest, physiotherapy and infiltration of the lateral axillary space.





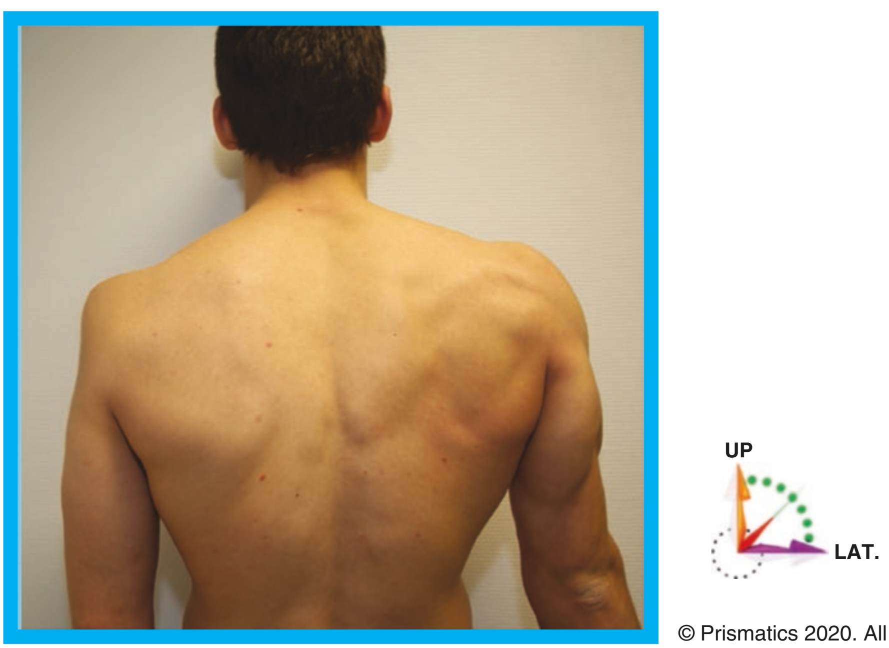


Figure Ax11. Pathologies of the axillary nerve. (**a**) 3D reconstruction of a complex fracture of the neck of humerus. From a clinical point of view, an anaesthesia of the stump and a deficit of abduction of the shoulder can be observed. (**b**) Patient showing a disuse atrophy of the left shoulder after a motorcycle accident.

Morphological Data: Sono Anatomy

The axillary nerve is a terminal branch of the posterior bundle of the brachial plexus, travelling to the dorsal surface of the axillary artery. It passes under the lower edge of the subscapularis muscle and binds the surgical neck of the humerus.

By reviewing the anatomical structures in a circular manner, from medial to lateral, the axillary vascular nerve bundle enters lateral axillary space. The limits of this space are the subscapularis and teres minor muscles at the top, the latissimus dorsi muscle at the bottom, the surgical neck of the humerus at the side, and the long head of the triceps brachii muscle medially.

The axillary nerve is most often damaged during shoulder trauma with anterointernal dislocation, fracture of the upper end of the humerus, and in these cases, the damage is rarely isolated. Isolated damage can occur during a direct impact or compression during perioperative surgery and also by extrinsic compressions of adjacent structures. Ductal syndrome in the axillary space is much rarer.

Installation

In the lateral axillary space, the former quadrilateral space, the patient is in a sitting position, the arm in internal rotation, forearm bent at 90°, hand resting on the opposite shoulder.

Equipment and Ultrasound Tracking

The skin marker is the posterior edge of the deltoid muscle at the level of the thorny bundle. The probe is in a parasagittal position, in the axis of the humerus.

Ultrasound Procedure

The humeral head is initially sought, followed by the surgical neck of the humerus, at the cutaneous level of the deltoid muscle (Figure Ax13), and a slight backward and downward translational movement (Figure Ax14) is then performed for vascular identification. The colour Doppler echo analyses posterior humeral circumflex artery flow, the axillary nerve being a satellite of this artery. Once identified, this artery must be placed at the centre of the ultrasound image.

On ultrasound detection, the deltoid muscle will be found laterally, the tendon of the teres minor muscle at the top and the humerus medially.

The nerve is rarely visible at this level, and search for adjacent muscle and vascular structures is indirect.

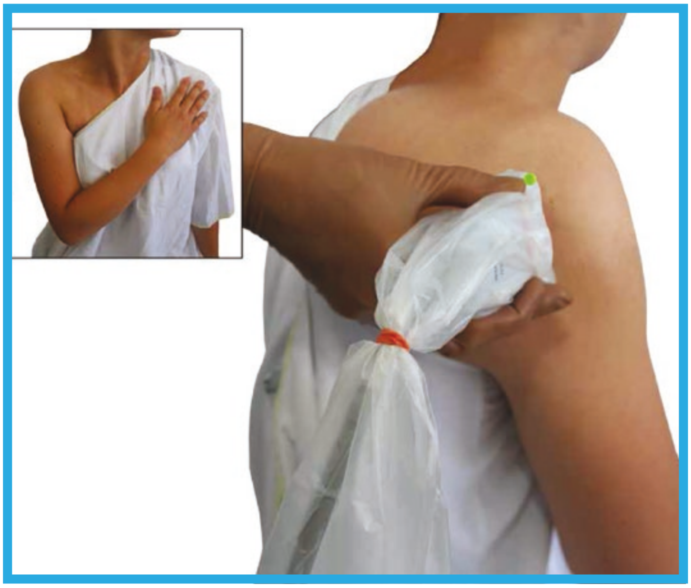
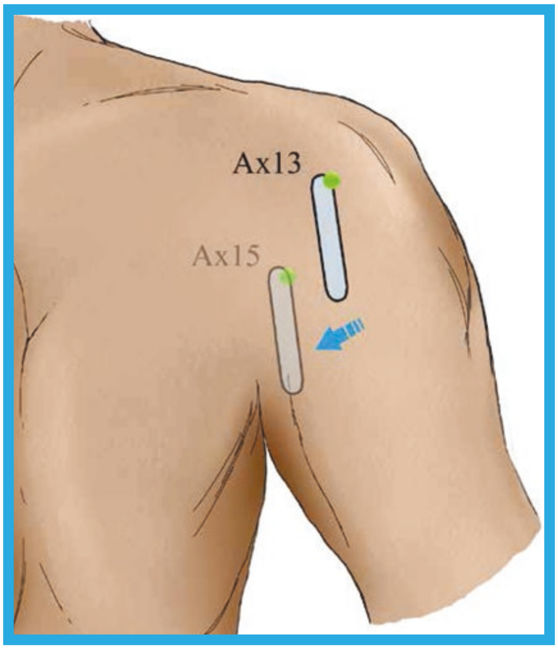
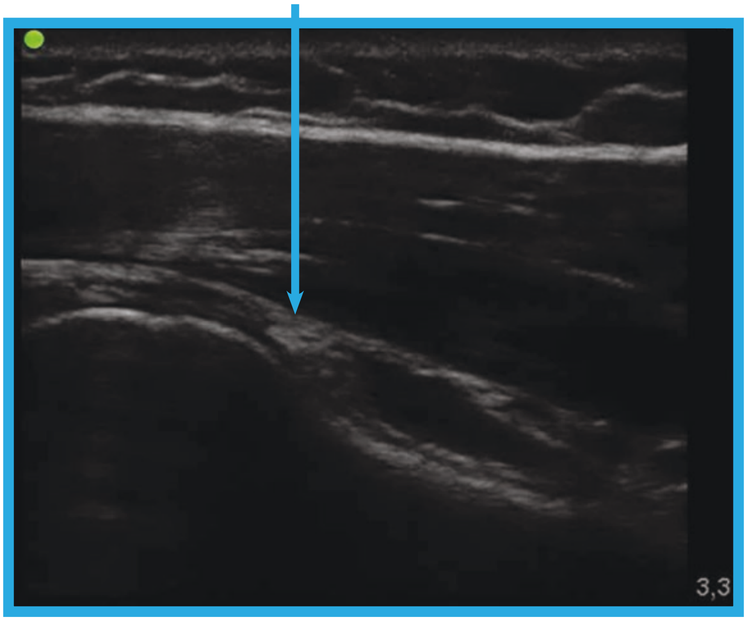


Figure Ax12. An overview of ultrasound positions to identify the axillary nerve.





1- Deltoid muscle

2- Intramuscular aponeurotic of the deltoid muscle

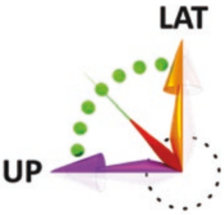
3- Long head of the triceps brachii muscle

4- Head of the teres minor muscle

5- Axillary nerve

6- Surgical neck of the humerus

7- Humeral head



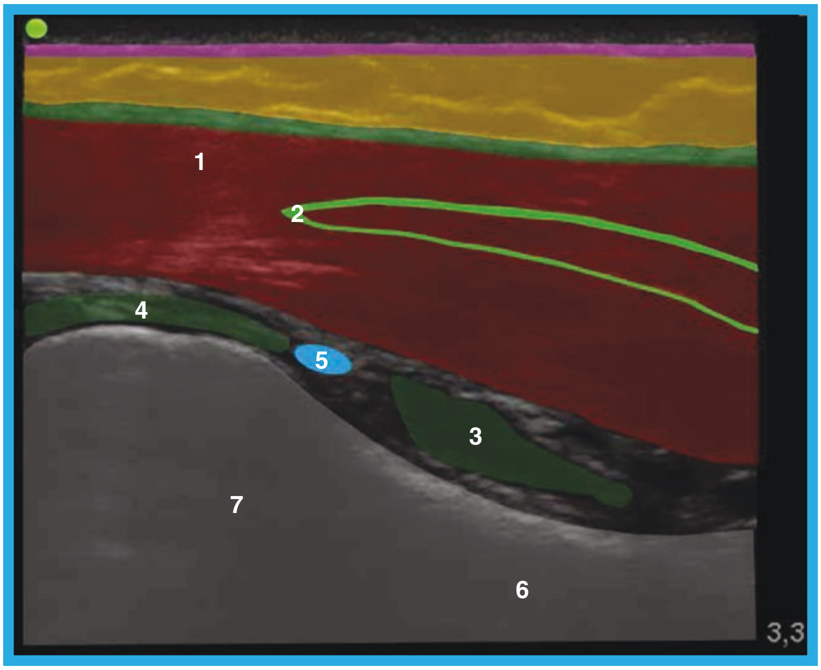


Figure Ax13. Ultrasound view of the axillary nerve at the shoulder level. Bone structure: surgical neck and humeral head.

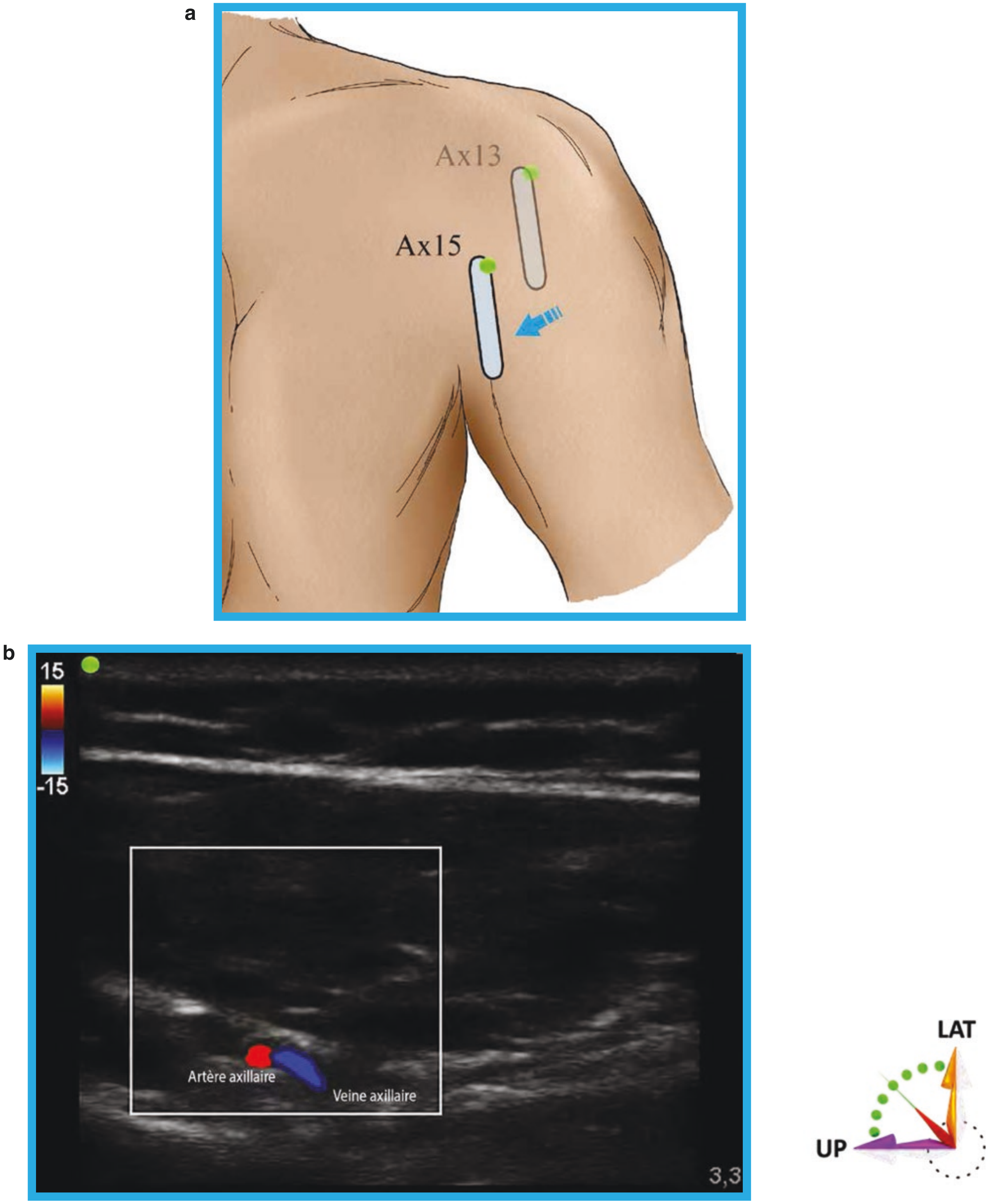
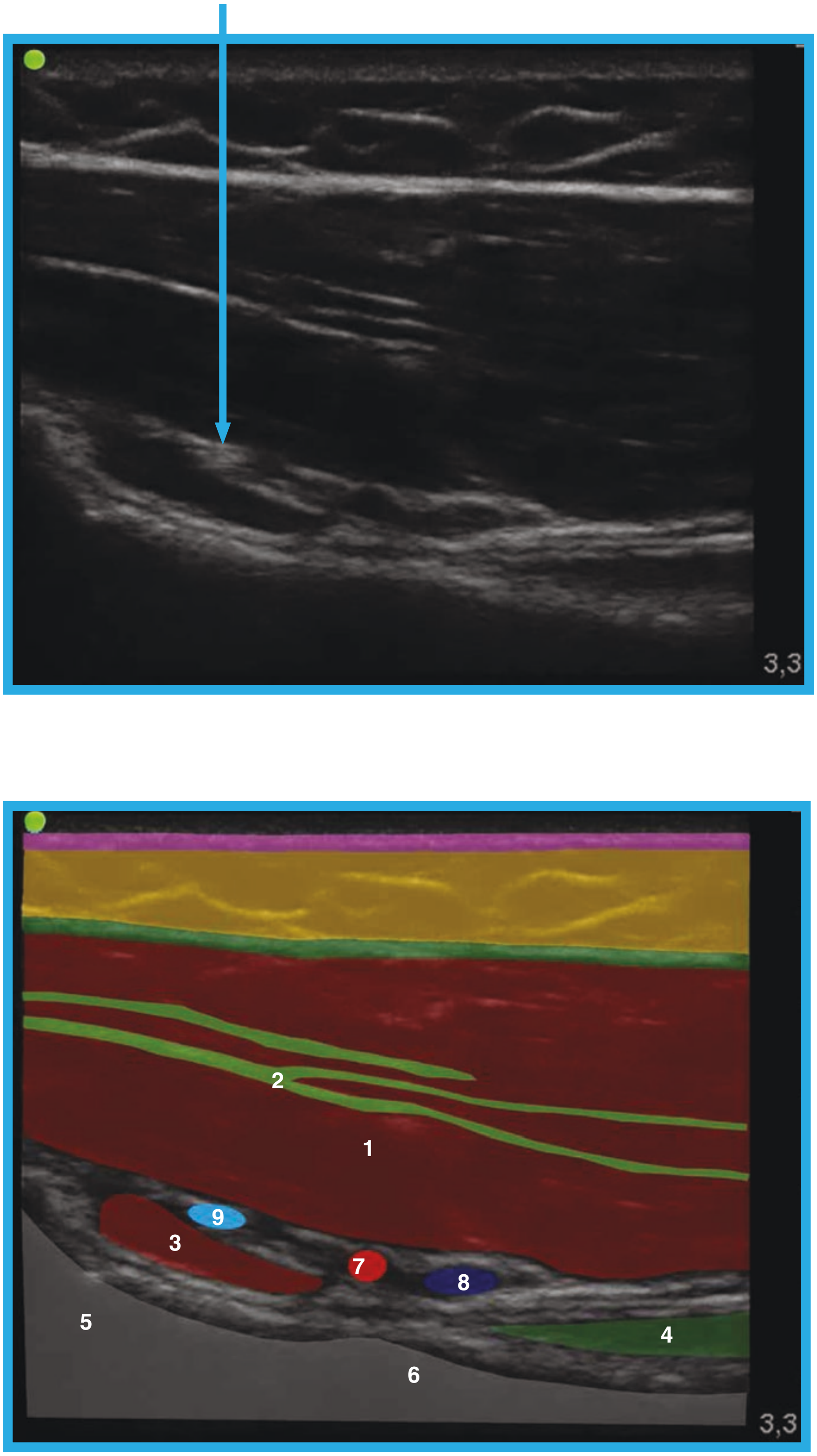

a
Ax13
Ax15
b
15
-15
Artère axillaire
Veine axillaire
3,3
LAT
UP

Figure Ax14. (**a**) An overview of ultrasound positions to identify the axillary nerve at the shoulder level. (**b**) Ultrasound identification of the posterior humeral circumflex artery using Doppler mode.



1- Deltoid muscle

2- Intramuscular aponeurotic of the deltoid muscle

3- Teres minor muscle

4- Long head of the triceps brachii muscle

5- Surgical neck of humerus

6- Humeral diaphysis

7- Axillary artery

8- Axillary vein

9- Axillary nerve

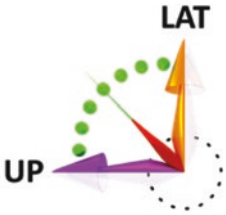


Figure Ax15. Ultrasound views of the axillary nerve at the shoulder level, junctions with rotator cuff muscle (teres minor muscle).

Interventional Procedure

Infiltration/Block Test

Indication
There are few specific applications of test blocks for this nerve, apart from analgesic or diagnostic purposes (e.g. to confirm a diagnosis of peripheral neuropathy or to verify the disappearance of pain in the sensory territory of the axillary nerve through anaesthetic infiltration).

In this context, gain in motor function (elevation and abduction of the shoulder) during sensitive anaesthesia, when motor inhibition is associated with myogenic pain of the stump in the deltoid and small circle, will be particularly appreciated.

Diagnostic or therapeutic infiltration will be performed under ultrasound guidance with an approach in the field (in plane) or outside the ultrasound field (out of plane). Neurodetection remains essential, as the nerve target is often not visible.

Comparative ultrasound can also identify deltoid amyotrophy or a change in arterial flow to colour Doppler during abduction and lateral rotation movements of the arm.

Out-of-Plane Technique

The purpose of the procedure is to position the target structure in the centre of the screen.

The main advantage of this technique is to limit the relatively painful muscle crossings of the needle.

The disadvantage of this technique is that it is impossible to follow the needle from its proximal end to its distal location, entailing a potential risk of vascular or nerve damage. In this context, hydrolocalization aimed at carrying out the most selective test block possible takes on its full meaning. It will be necessary to ensure that it is hydrolocalized with saline or glucose infusion 5% (G5%) without using a local anaesthetic before coming into contact with the nerve. Given the calibre of this nerve, a final check by electrostimulation will be essential.

In-Plane Technology

This technique will be particularly useful for people who are not very muscular in the deltoid.

It is achieved by positioning the ultrasound probe a little higher and proximal to access the nerve by pricking upwards from the bottom towards the humeral head (Figure Ax16b). Indeed, the opposite (obliquity of the needle from top to bottom) is more complicated if the ultrasound probe remains in place as in the previous figure (Figure Ax16a), there is only a small space and therefore very little room for manoeuvre between the bone relief (humeral head and distal end of the acromion) and the ultrasound probe.

The main advantage of this technique is that there is no need for at-times painful hydrolocalization, whilst the needle is visualized in its entirety with relatively direct access to the target.

The disadvantage of this technique pertains to the deltoid of a relatively muscular patient, of with a transmuscular passage that can sometimes be relatively painful.

Peripheral Nerve Stimulation

The analgesic technique for peripheral stimulation of this nerve is not very widespread due to risk of mobilization of the lead. Stimulation of the brachial plexus in C5–C6 to cover the same areas is most often preferred.

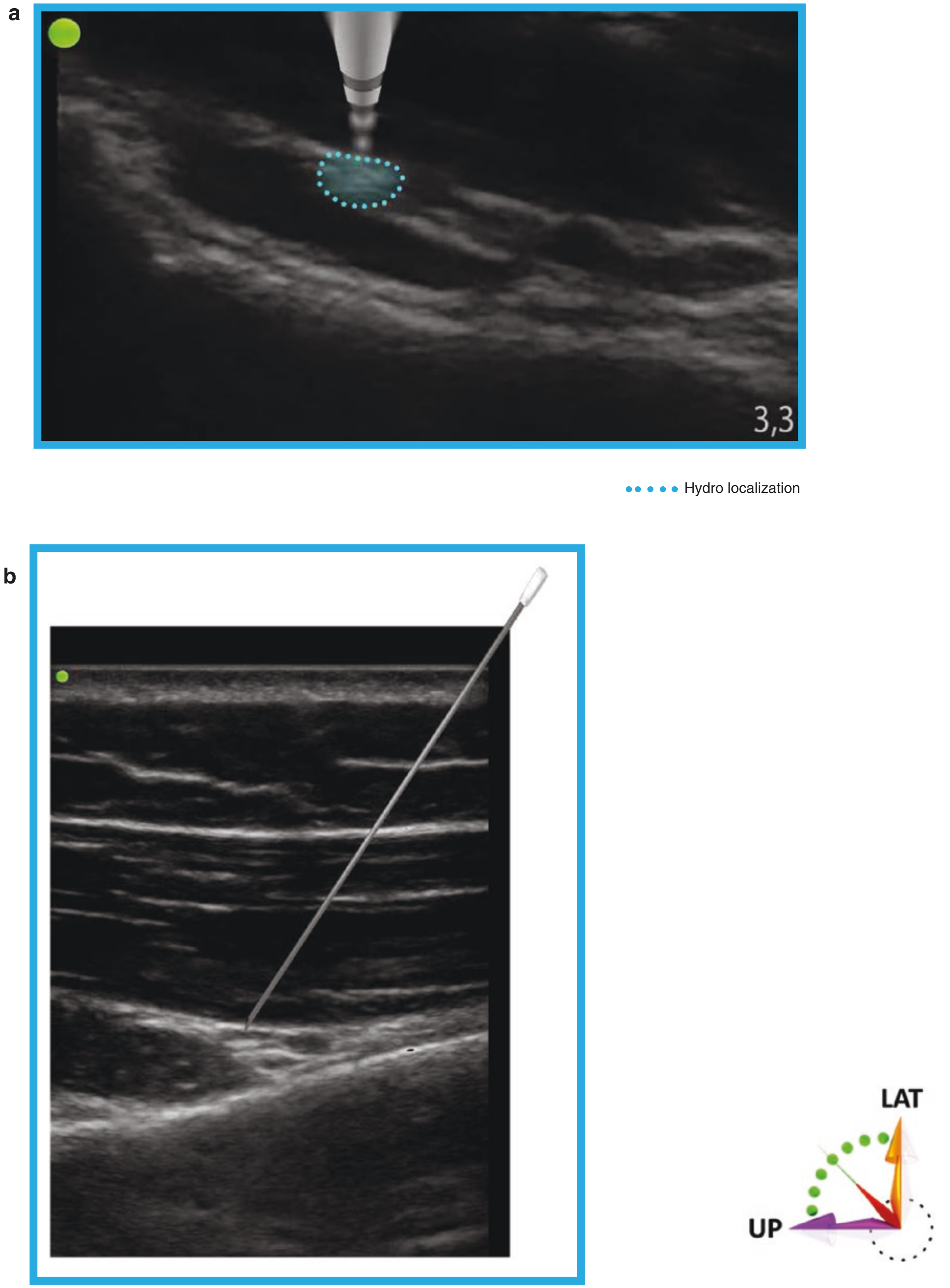

a
3,3
•••• Hydro localization
b
LAT
UP

Figure Ax16. Axillary nerve anaesthetic block; (**a**) Out-of-plane technique with hydrodissection. (**b**) In-plane technique, echographic probe 13-6, 25 mm width.

Surgical Procedure

Surgical Indications

Isolated damage to this nerve is quite rare. Its lesions are most often occasioned by more or less complete paralysis of the post-traumatic brachial plexus. Nerve repair can be indicated in the context of direct or indirect nerve injuries.

It should be understood that the axillary nerve is vulnerable when it passes through the posterior surface of the upper third of the humerus, in its furrow. Its onset is therefore mainly due to fractures of the humerus or dislocations of the humeral head.

Surgical Approaches

Skin Incision

The nerve can be explored either anteriorly or posteriorly.

The anterior pathway has the advantage of exposing the nerve from its origin on the posterior bundle of the brachial plexus to the lateral axillary space outside. The disadvantage is that it does not allow the nerve to be further explored.

This anterior pathway is similar to the classical keyboard approach of the brachial plexus.

The incision additionally and subclavicularly exposes the brachial plexus. It begins at the posterior edge of the sternocleidomastoid muscle, running along the clavicle. It extends to the lower edge of the clavicle, parallel to the clavicle, and curves further outwards at the deltopectoral groove. Exposure of the entire plexus is remarkable, but this incision is relatively aesthetically damaging.

Nervous Exposure

The posterior plexus bundle is easily located behind and above the axillary artery, beginning dissection above the lateral bundle. The vascular axis will be followed towards the distality, taking care to protect the nerves of the subscapularis and latissimus dorsi muscles until the axillary nerve is highlighted. It moves back and forth near the lower posterior part of the scapulohumeral joint capsule, accompanied by the posterior circumflex vessels. In the quadrilateral space, limited outside by the surgical neck of the humerus and inside by the long portion of the triceps, the nerve will be found between the small circle at the top and the large circle at the bottom. Unfortunately, it will not be followed any farther by the same method.

The posterior approach, shown on this double page, should be preferred if the objective is to approach the nerve in its distal part (Figures Ax17 and Ax18).

A curved incision centred on the spine of the scapula is used to move outwards towards the acromion and join the posterior median axis of the arm to the delto-municipal groove at the bottom and laterally. The posterior edge of the deltoid muscle is located and pushed upwards and sideways using a Farabeuf retractor to discover infraspinatus fascia (Figure Ax18). It is then incised to locate the lower edge of the small round muscle and the upper edge of the large round muscle in the lateral axillary space.

The axillary nerve is approached inside the lateral leader of the brachial triceps and can be followed to the humerus neck, along with the posterior circumflex vessels, located above and outside the nerve.

Technical Pitfalls

They essentially concern the anterior approach:

- Unsightly or even retractable scar.
- If an osteotomy of the collarbone is necessary, particular care should be taken to ensure that there is a risk of pseudoarthrosis and osteomyelitis.
- Vascular wound of the axillary axis.

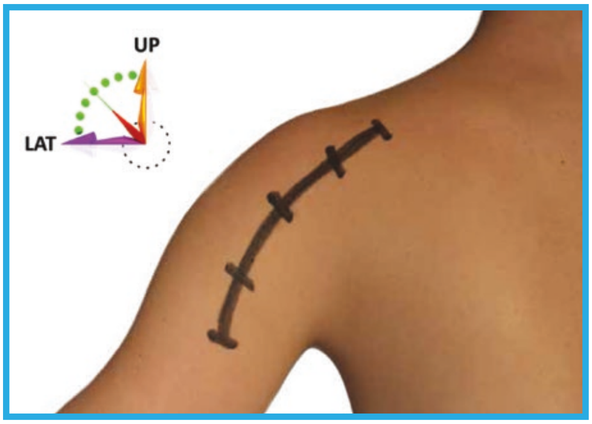


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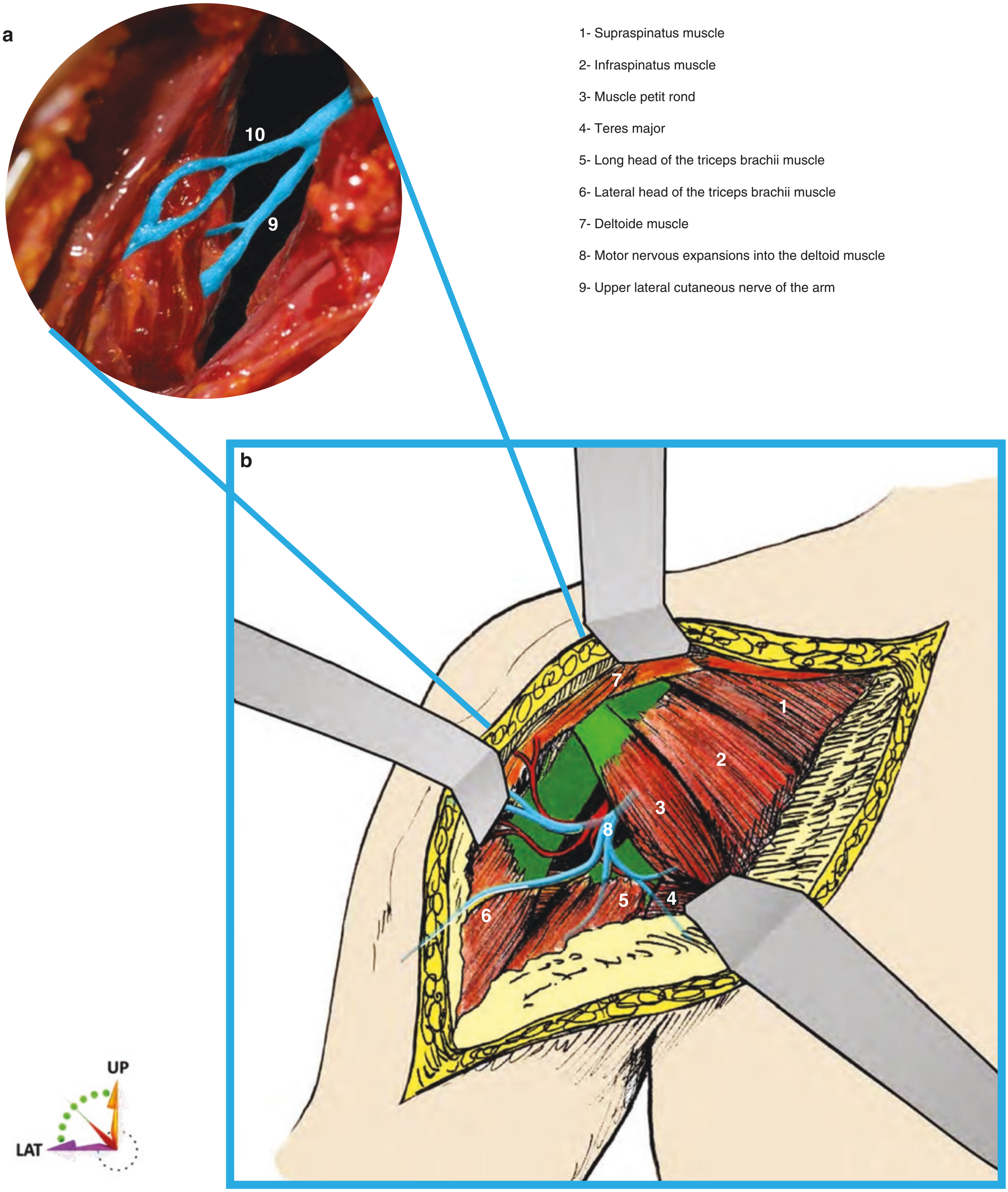
Figure Ax17. Axillary nerve surgical approach. Posterior incision (left shoulder).



1- Supraspinatus muscle
2- Infraspinatus muscle
3- Muscle petit rond
4- Teres major
5- Long head of the triceps brachii muscle
6- Lateral head of the triceps brachii muscle
7- Deltoide muscle
8- Motor nervous expansions into the deltoid muscle
9- Upper lateral cutaneous nerve of the arm

Figure Ax18. (**a**) Axillary nerve posterior surgical approach at the shoulder level. Zoom on the sensitive and motor branches. (**b**) Motor distribution of the axillary nerve at the deep and posterior face of the deltoid muscle.

The Axillary Nerve

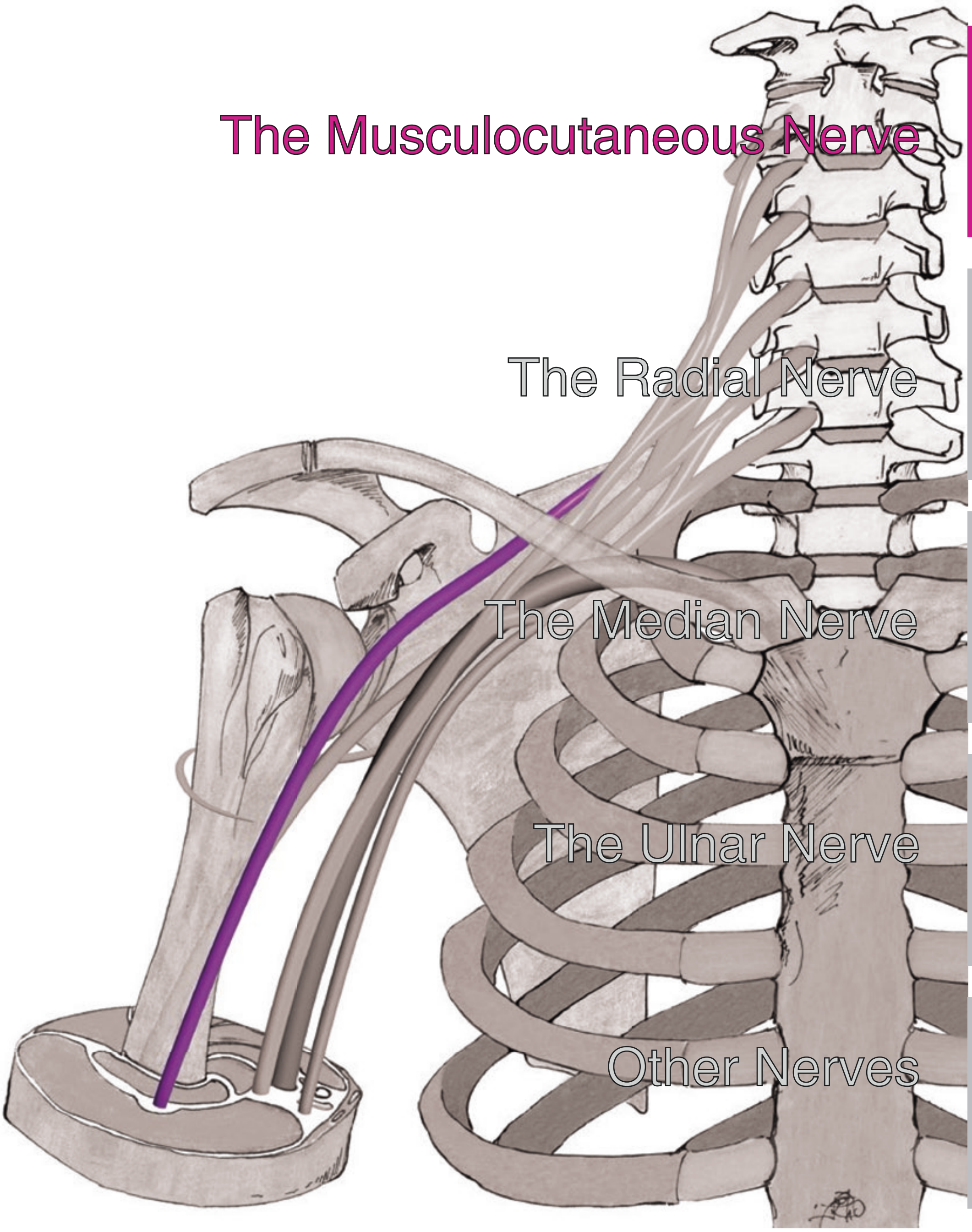
The Musculocutaneous Nerve

The Radial Nerve

The Median Nerve

The Ulnar Nerve

Other Nerves



The Musculocutaneous Nerve

Morphological Data

The musculocutaneous nerve is a terminal branch of the brachial plexus. Its purpose is to allow the forearm's flexion; it is also responsible for the sensitive innervation of the forearm's lateral face until the thumb. It is a mixed nerve with its main part coming from the superior trunk of the brachial plexus and its minor part coming from the reunion of the anterior divisions of the middle trunk of the brachial plexus.

Origin

The musculocutaneous nerve is made up of neurofibres that find their origin in the C5 and C6 roots of the brachial plexus (Figure MC1). It starts outside and in front of the axillary artery. It constitutes a terminal branch of the lateral bundle of the brachial plexus.

At this level, it faces the axillary artery medially. The median nerve can be found in front of the artery, and the radial nerve behind it.

Path

After going past the apex of the coracoid process, the nerve heads slightly towards the outer part to go through the two heads of the coracobrachialis muscle, generally at a distance equivalent to four times the width of a finger under the apex of the process. The entry point of the nerve in the muscle can vary with a division of the nerve situated above and several motor branches already given off at this level (Figure MC2).

After going through the coracobrachialis muscle, the nerve leaves on its anterior and lateral face in order to penetrate the middle part of the arm, making its way between the biceps brachii muscle and the lower extremity of the coracobrachialis muscle. It then follows the brachial muscle in a groove situated between this muscle laterally and the biceps medially (Figures MC3, MC9 and MC11).

At the inferior third of the arm, it makes its way on the posterior face of the biceps brachii until the antecubital area, at the level of the lateral bicipital groove. At this point, the musculocutaneous nerve faces the tendon of the biceps brachii muscle medially and the brachioradialis muscle laterally (Figures MC5, MC10 and MC12).

The musculocutaneous nerve ends when it becomes the lateral cutaneous nerve of the forearm which is purely sensitive after having given off all of its motor collateral branches earlier. This transition happens where the musculocutaneous nerve emerges at the lateral edge of the biceps brachii muscle, generally at the level of the lateral epicondyle of the humerus (Figures MC2 and MC3).

Neurovascular Relations

At its origin, the musculocutaneous nerve faces the axillary artery.

In the arm, it moves away laterally from the brachial artery, which it faces remotely (Figure MC4).

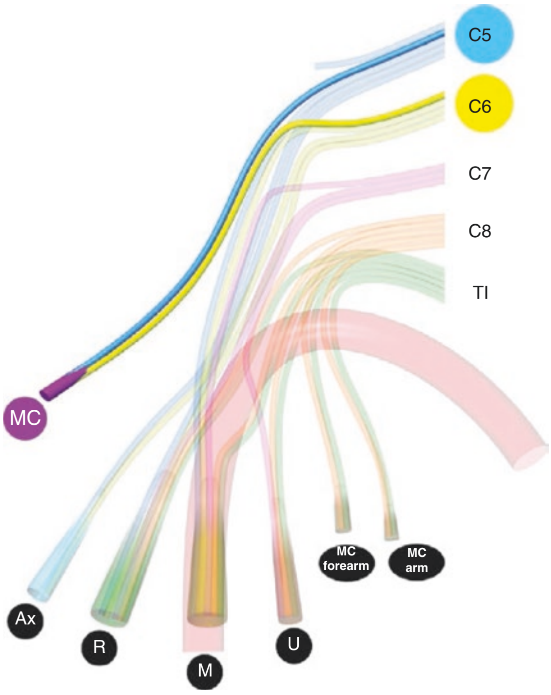


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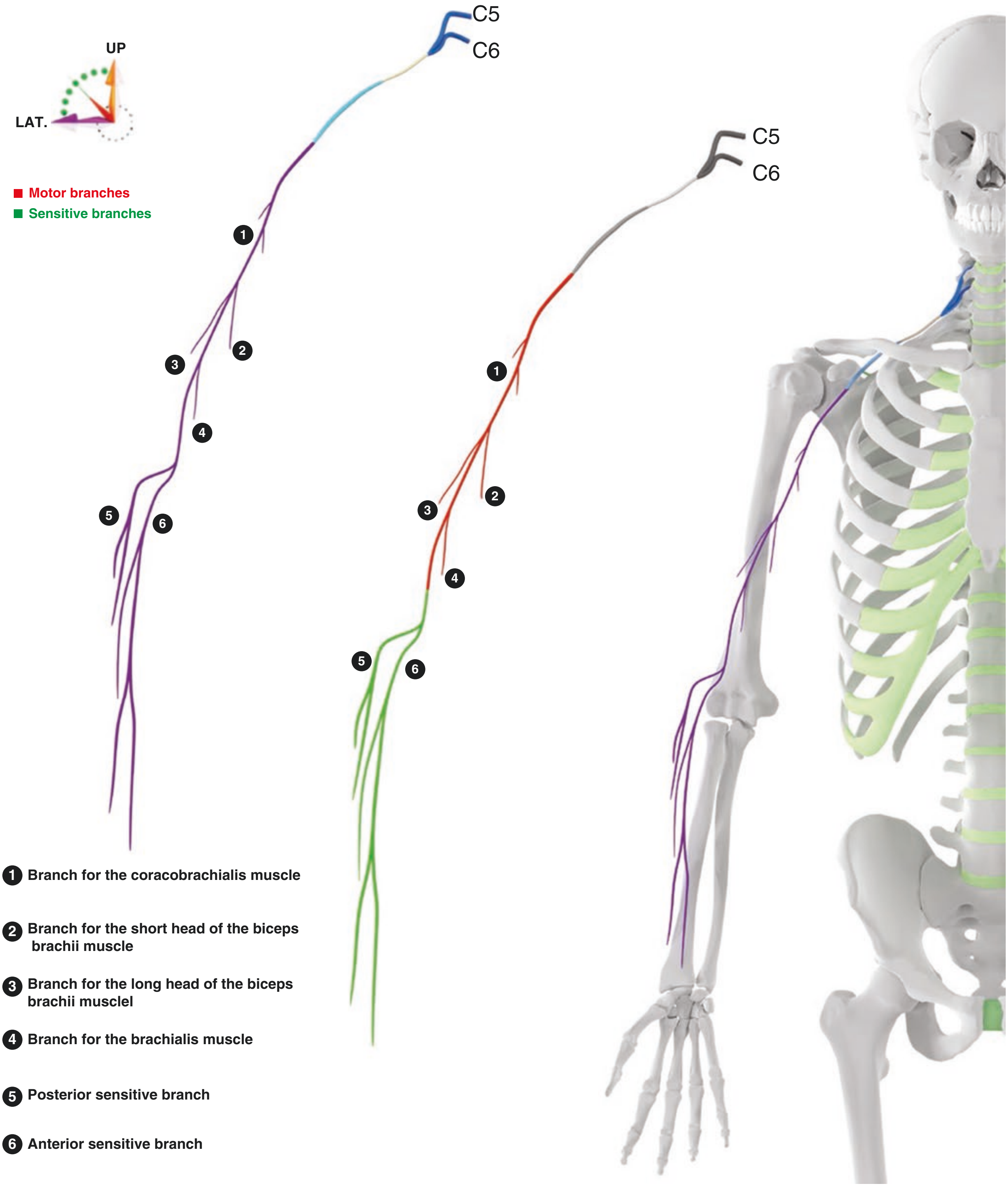
Figure MC1. Origin of the musculocutaneous nerve.

Electronic Supplementary Material The online version of this chapter (https://doi.org/10.1007/978-3-030-49179-6_6) contains supplementary material, which is available to authorized users.


UP
LAT.
🟥 Motor branches
🟩 Sensitive branches
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C6
C5
C6
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6
1
2
3
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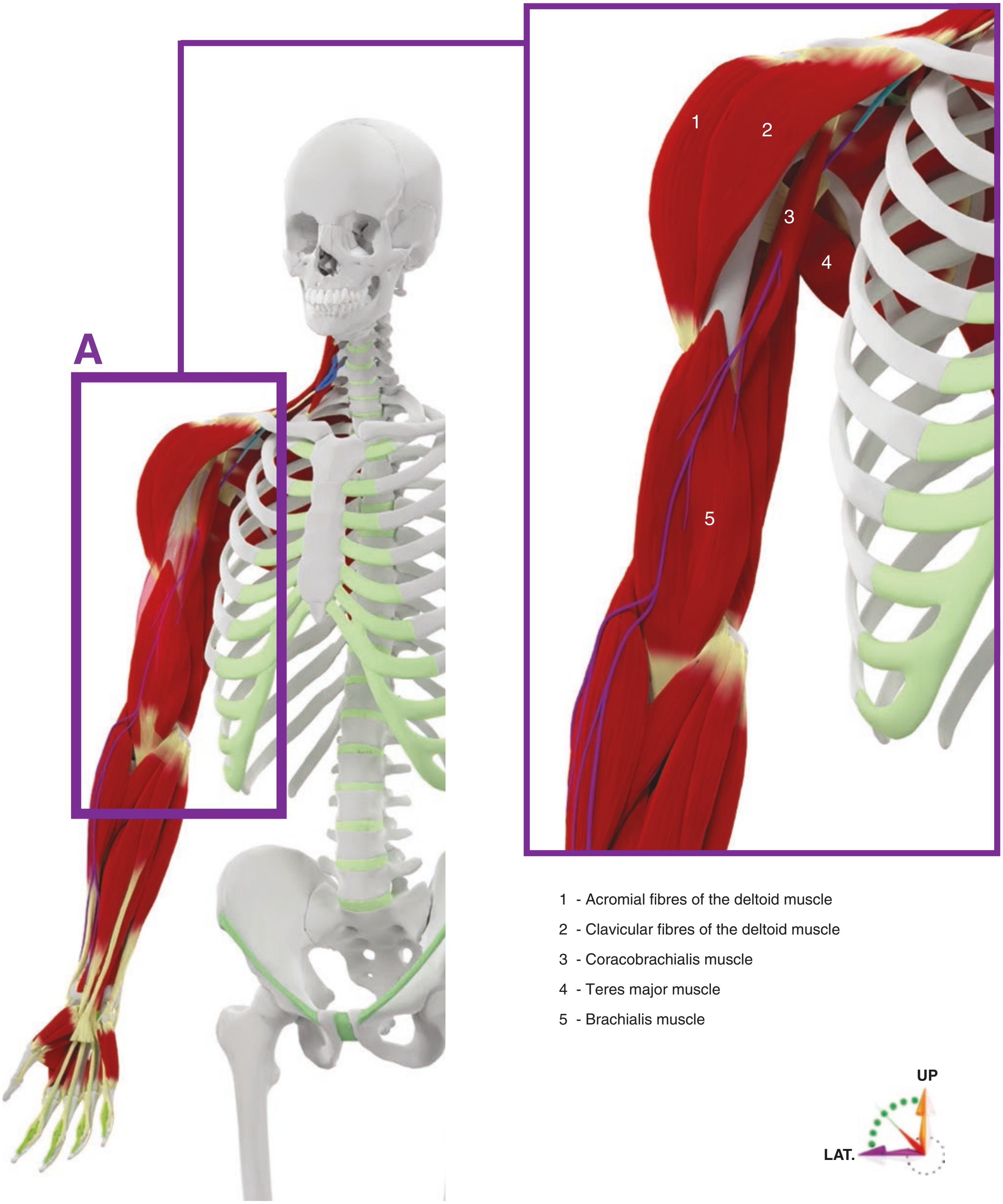
5
6

1. **Branch for the coracobrachialis muscle**
2. **Branch for the short head of the biceps brachii muscle**
3. **Branch for the long head of the biceps brachii musclel**
4. **Branch for the brachialis muscle**
5. **Posterior sensitive branch**
6. **Anterior sensitive branch**

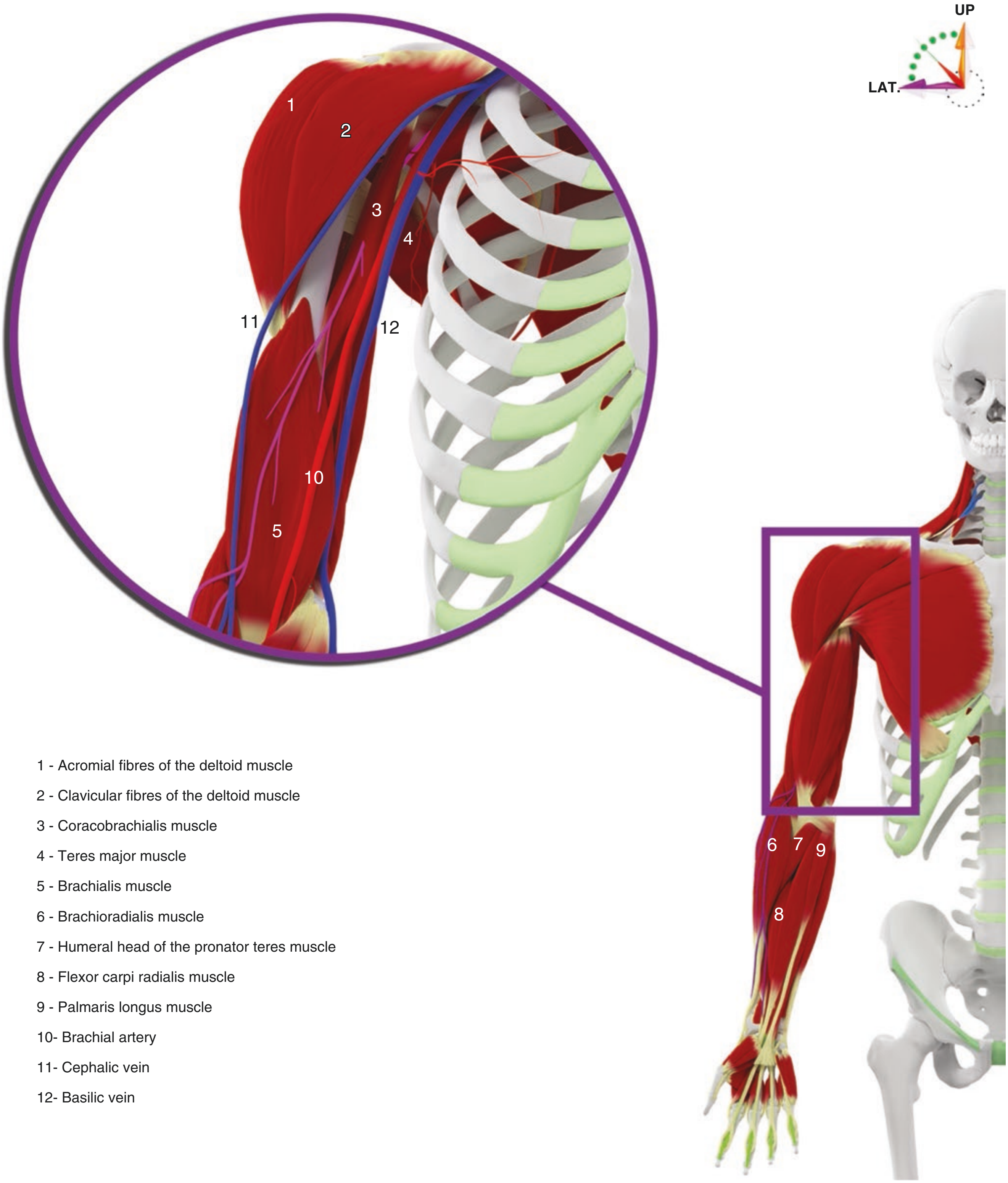
Figure MC2. Distribution of the musculocutaneous nerve and its relations with bones.

The Musculocutaneous Nerve



1 - Acromial fibres of the deltoid muscle
2 - Clavicular fibres of the deltoid muscle
3 - Coracobrachialis muscle
4 - Teres major muscle
5 - Brachialis muscle

Figure MC3. Relations of the musculocutaneous nerve with muscles in the arm.



1 - Acromial fibres of the deltoid muscle
2 - Clavicular fibres of the deltoid muscle
3 - Coracobrachialis muscle
4 - Teres major muscle
5 - Brachialis muscle
6 - Brachioradialis muscle
7 - Humeral head of the pronator teres muscle
8 - Flexor carpi radialis muscle
9 - Palmaris longus muscle
10- Brachial artery
11- Cephalic vein
12- Basilic vein

Figure MC4. Neurovascular relations as the musculocutaneous nerve goes through the coracobrachialis muscle.

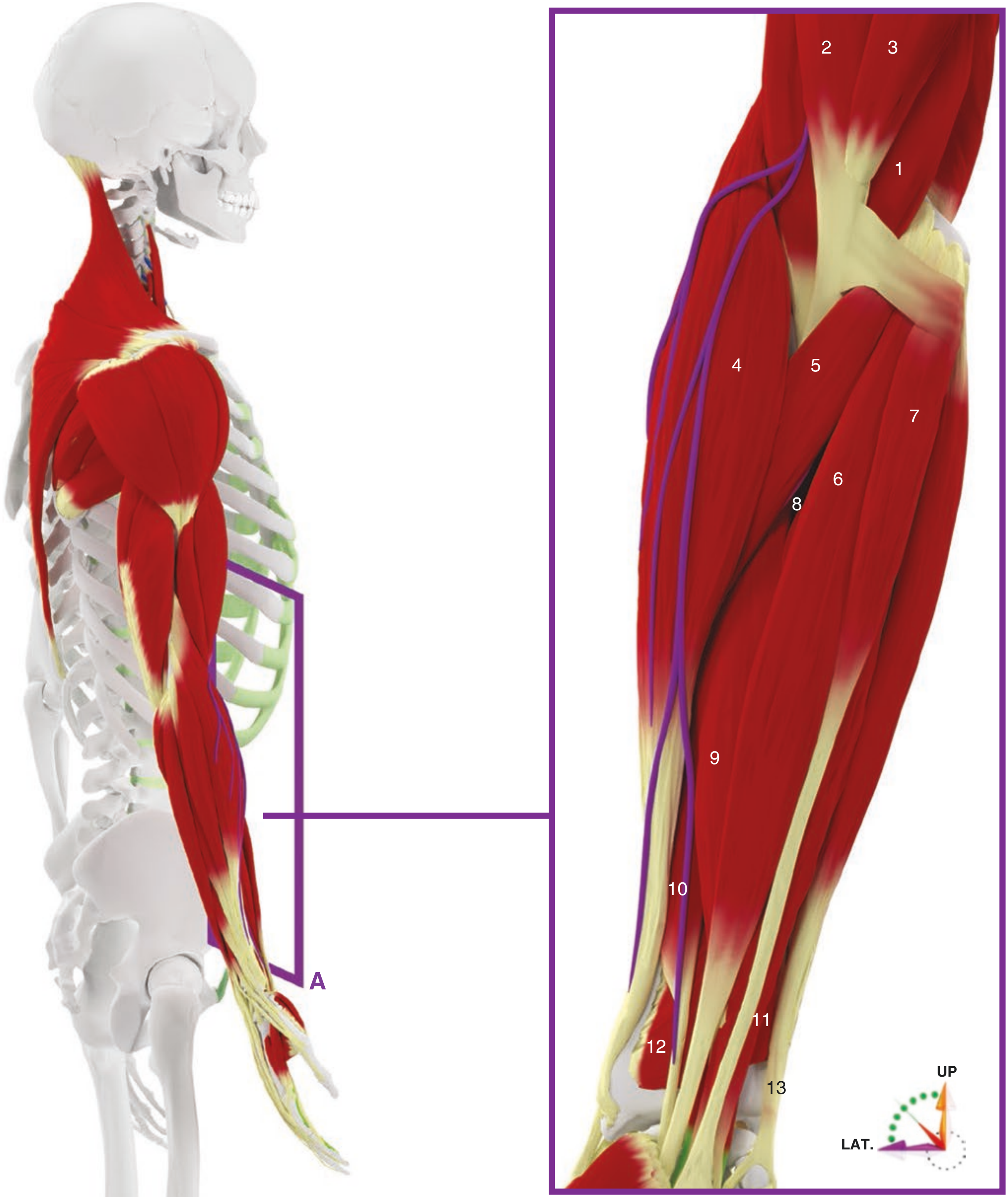

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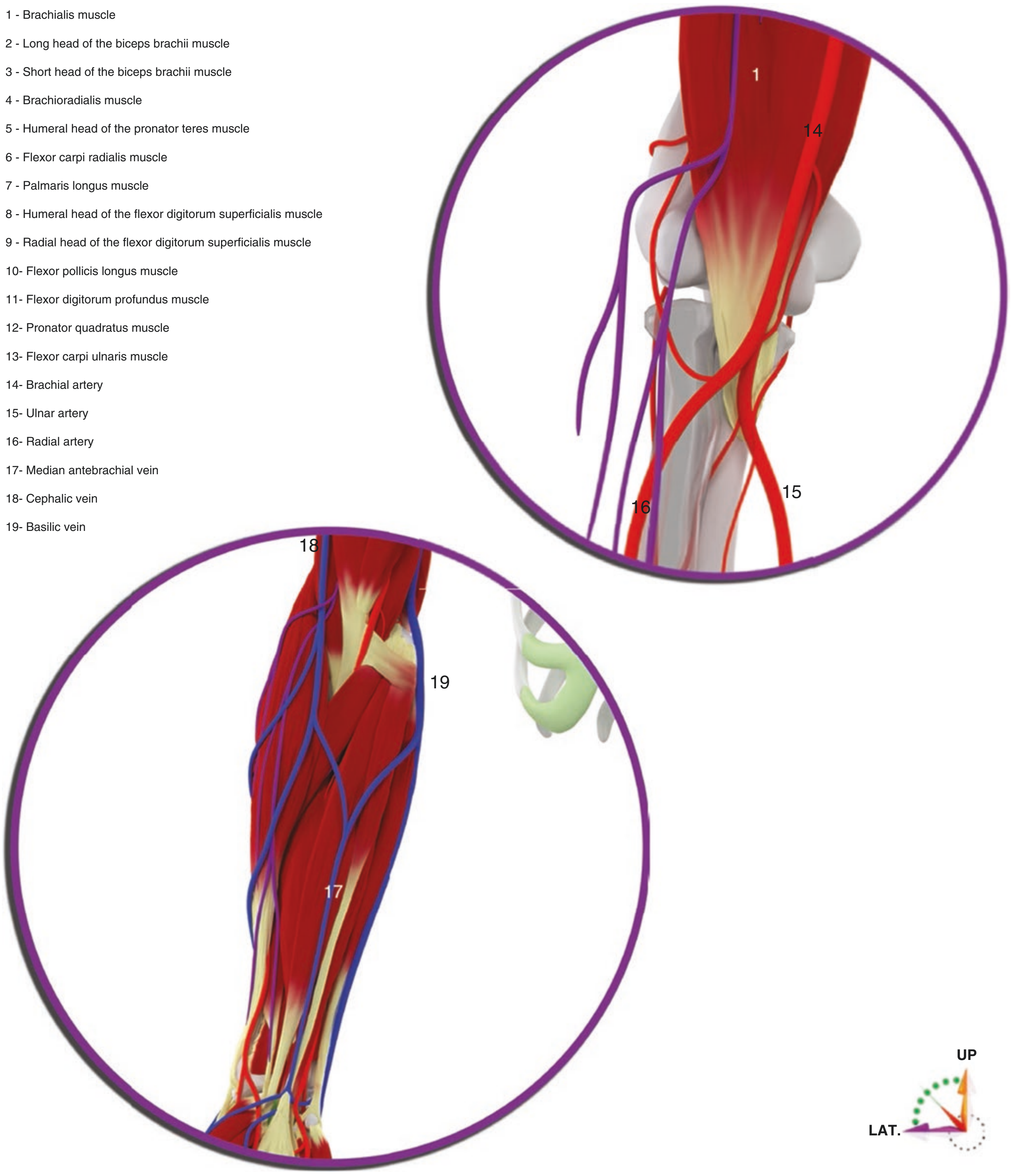
Figure MC5. Relations of the musculocutaneous nerve in the forearm.



1 - Brachialis muscle
2 - Long head of the biceps brachii muscle
3 - Short head of the biceps brachii muscle
4 - Brachioradialis muscle
5 - Humeral head of the pronator teres muscle
6 - Flexor carpi radialis muscle
7 - Palmaris longus muscle
8 - Humeral head of the flexor digitorum superficialis muscle
9 - Radial head of the flexor digitorum superficialis muscle
10- Flexor pollicis longus muscle
11- Flexor digitorum profundus muscle
12- Pronator quadratus muscle
13- Flexor carpi ulnaris muscle
14- Brachial artery
15- Ulnar artery
16- Radial artery
17- Median antebrachial vein
18- Cephalic vein
19- Basilic vein

Figure MC6. Sensitive terminal branches of the musculocutaneous nerve and neurovascular relations.

The Musculocutaneous Nerve

In the elbow, the musculocutaneous nerve lies against the brachialis muscle at the level of its distal insertions. The radial recurrent artery is located behind these, sticking closely to the lateral epicondyle (Figure MC6).

The division branches of the lateral cutaneous nerve of the forearm, itself being a terminal branch of the musculocutaneous nerve, are situated in the upper layers and part from the main arteries of the arm (Figure MC6).

Collateral Branches

The musculocutaneous nerve innervates the following branches in its path:

- A diaphyseal branch for the humerus.
- Vascular branches, heading towards the axillary artery and the brachial artery.
- Muscle branches linked to the brachial muscle, biceps brachii and coracobrachialis muscle. The latter generally receives two branches, an upper branch that parts from the nerve near its origin point and a lower branch, more remote (Figures MC2 and MC13).

Terminal Branches

The musculocutaneous nerve ends when it goes through the biceps brachii's aponeurosis at the level of the elbow pit and then becomes the lateral cutaneous nerve of the forearm.

The lateral cutaneous nerve of the forearm consists of two branches, one being anterior and the other posterior. They both make their way along the cephalic vein mostly to innervate the lateral face of the forearm (Figures MC6, MC14 and MC15).

Motor Function

The musculocutaneous nerve innervates the coracobrachialis, biceps brachii and brachial muscles. It is thus meant for the flexion of the forearm on the arm and secondarily for supination thanks to the innervation of the biceps brachii muscle (Figures MC7 and MC8).

Sensitive Function

The sensitive function of the nerve is assured by its terminal branch, the lateral cutaneous nerve of the forearm. Its anterior branch heads towards the thenar eminence but does not take care of its innervation and its posterior branch to the posterior and lateral face of the forearm (Figure MC8).

Anastomoses

The median nerve receives, in most cases, a branch of the musculocutaneous nerve. This nerve achieves an anastomosis at the level of the forearm with the radial nerve.

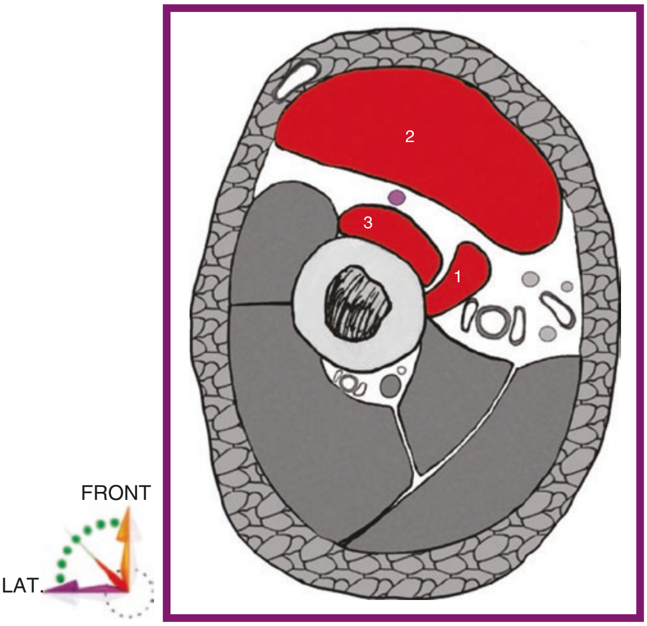


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Figure MC7. Motor innervation of the musculocutaneous nerve.

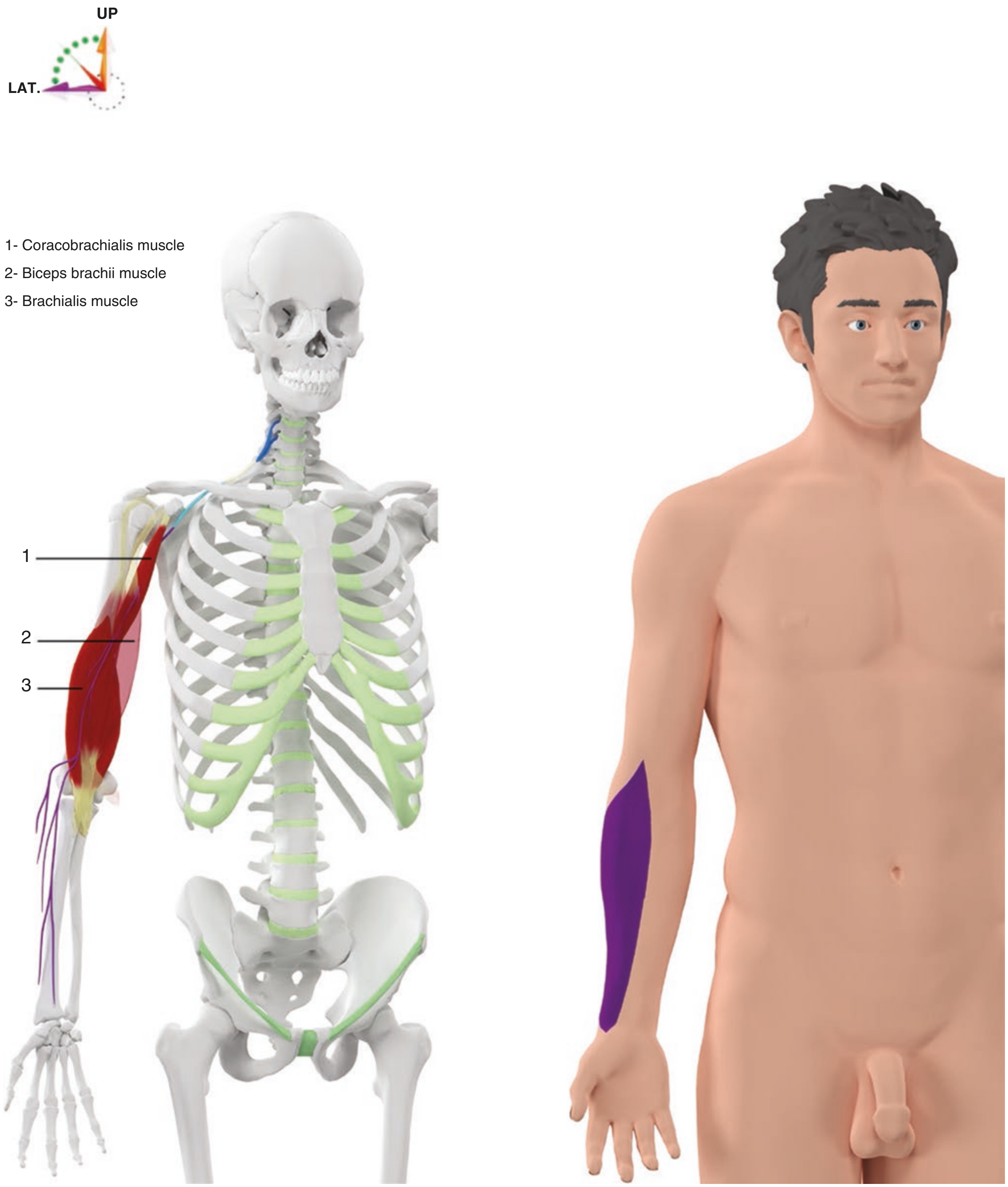
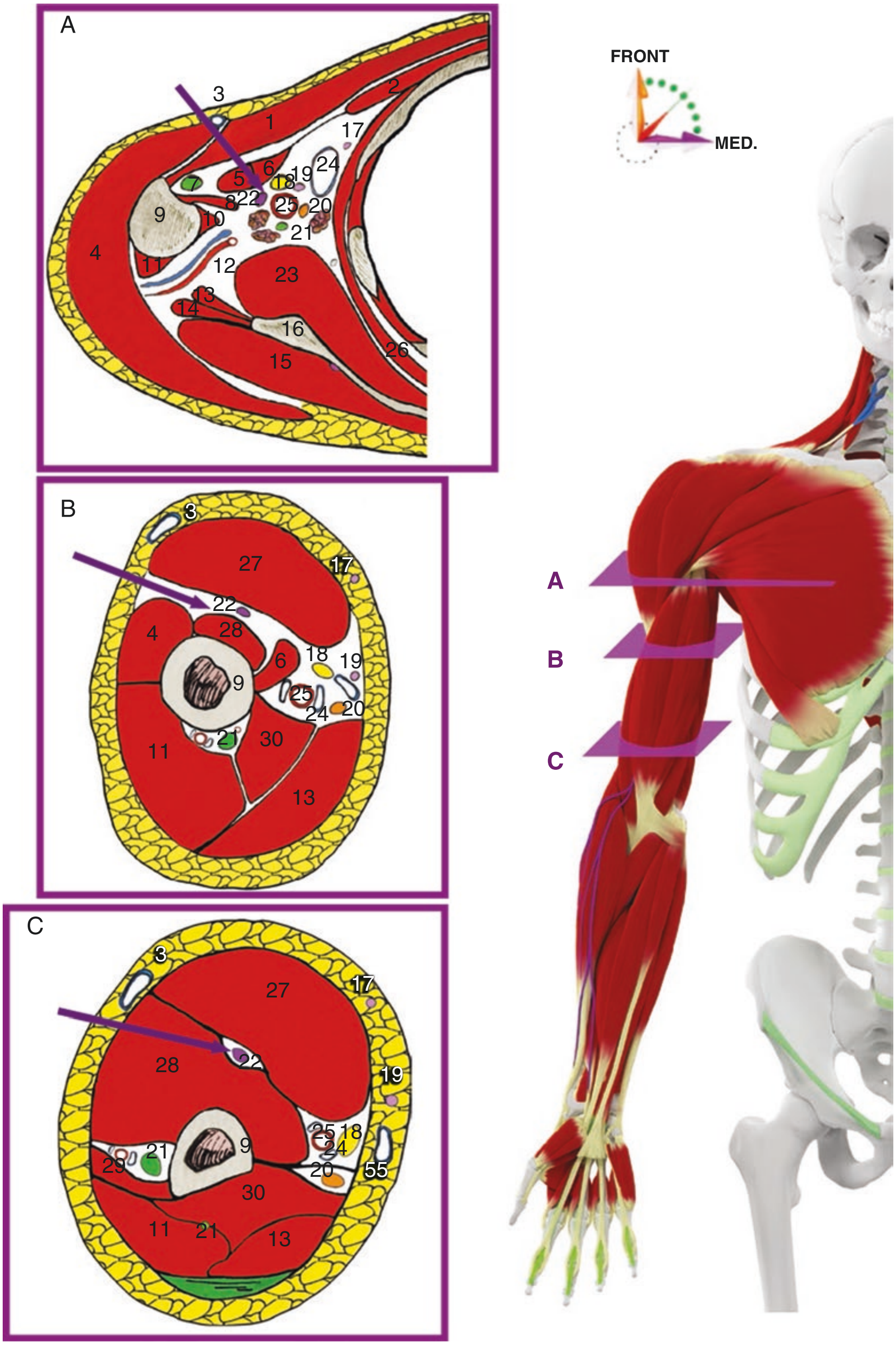

UP
LAT.
1- Coracobrachialis muscle
2- Biceps brachii muscle
3- Brachialis muscle
1
2
3

Figure MC8. Motor (**a**) and sensitive (**b**) innervation of the musculocutaneous nerve.

1- Pectoralis major muscle
2- Pectoralis minor muscle
3- Cephalic vein
4- Deltoid muscle
5- Short head of the biceps brachii muscle
6- Coracobrachialis muscle
7- Tendon of the long head of the biceps brachii muscle
8- Latissimus dorsi muscle
9- Humerus
10- Teres major muscle
11- Lateral head of the triceps brachii muscle
12- Circumflex artery and axillary nerve
13- Long head of the triceps brachii muscle
14- Teres minor muscle
15- Infraspinatus muscle
16- Scapula
17- Medial cutaneous nerve of arm
18- Median nerve
19- Medial cutaneous nerve of forearm
20- Ulnar nerve
21- Radial nerve
22- Musculocutaneous nerve
23- Subscapularis muscle
24- Brachial vein
25- Brachial artery
26- Serratus anterior muscle
27- Biceps brachii muscle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13
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MED.
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Figure MC9. Relations of the musculocutaneous nerve in the arm, axial views.

28- Brachialis muscle
29- Brachioradialis muscle
30- Medial head of the triceps brachii muscle
31- Extensor carpi radialis longus muscle
32- Extensor carpi radialis brevis muscle
33- Tendon of epicondyle muscles
34- Anconeus muscle
35- Olecranon
36- Tendon of the triceps brachii muscle
37- Tendon of the median epycondylian muscles
38- Pronator teres muscle
39- Ulna
40- Radius
41- Palmaris longus muscle
42- Flexor carpi radialis muscle
43- Flexor digitorum superficialis muscle
44- Flexor digitorum profundus muscle
45- Flexor pollicis longus muscle
46- Flexor carpi ulnaris muscle
47- Abductor pollicis longus muscle
48- Extensor pollicis brevis muscle
49- Extensor pollicis longus muscle
50- Extensor digitorum muscle
51- Extensor digiti minimi muscle
52- Extensor carpi ulnaris muscle
53- Extensor indicis muscle
54- Median vein of the forearm
55- Basilic vein

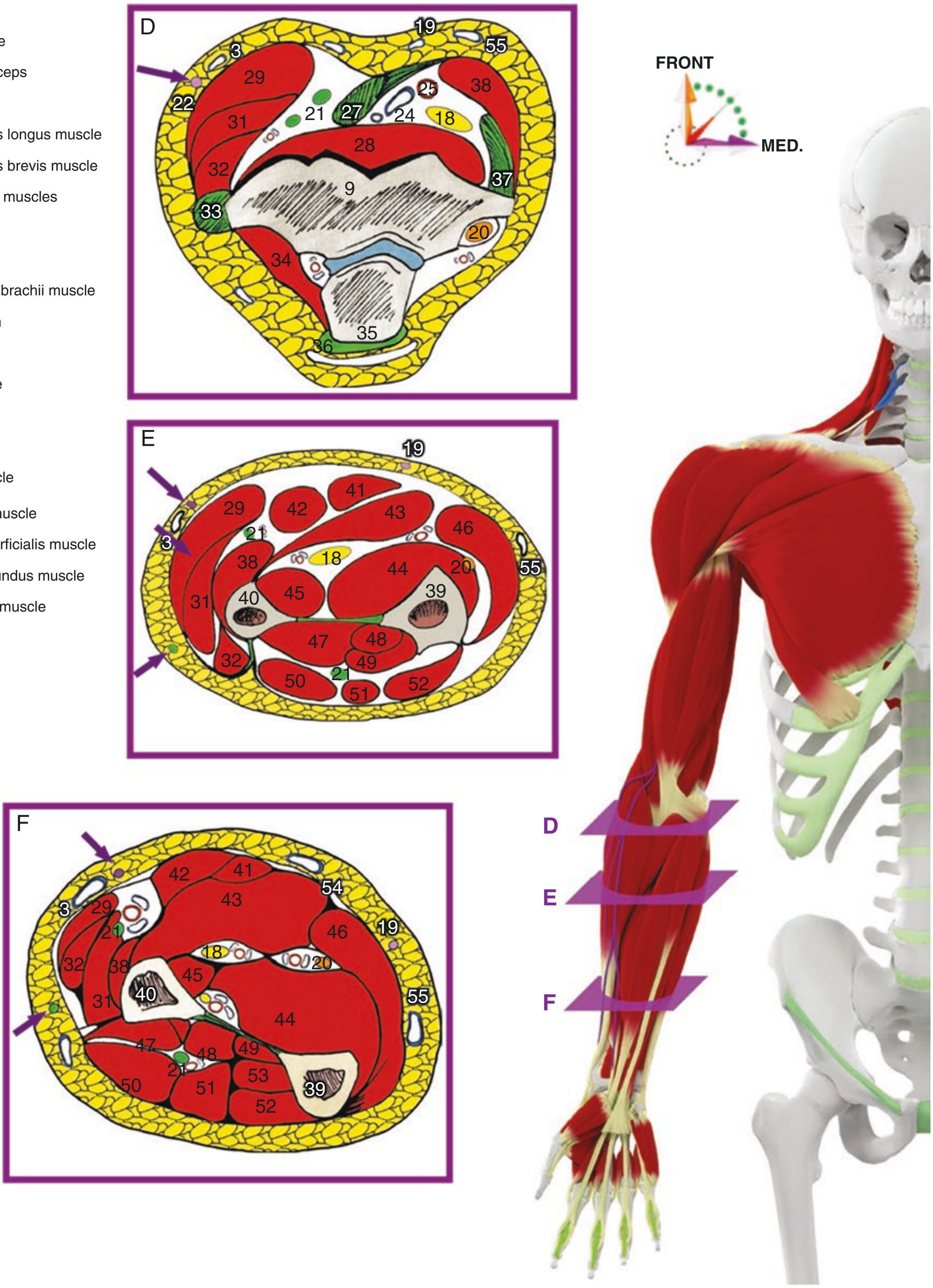
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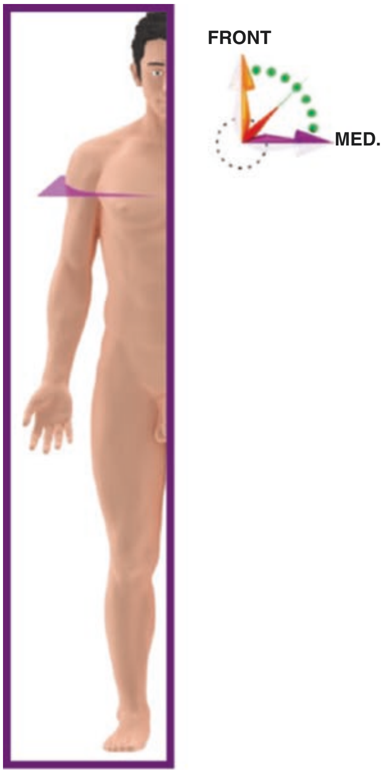
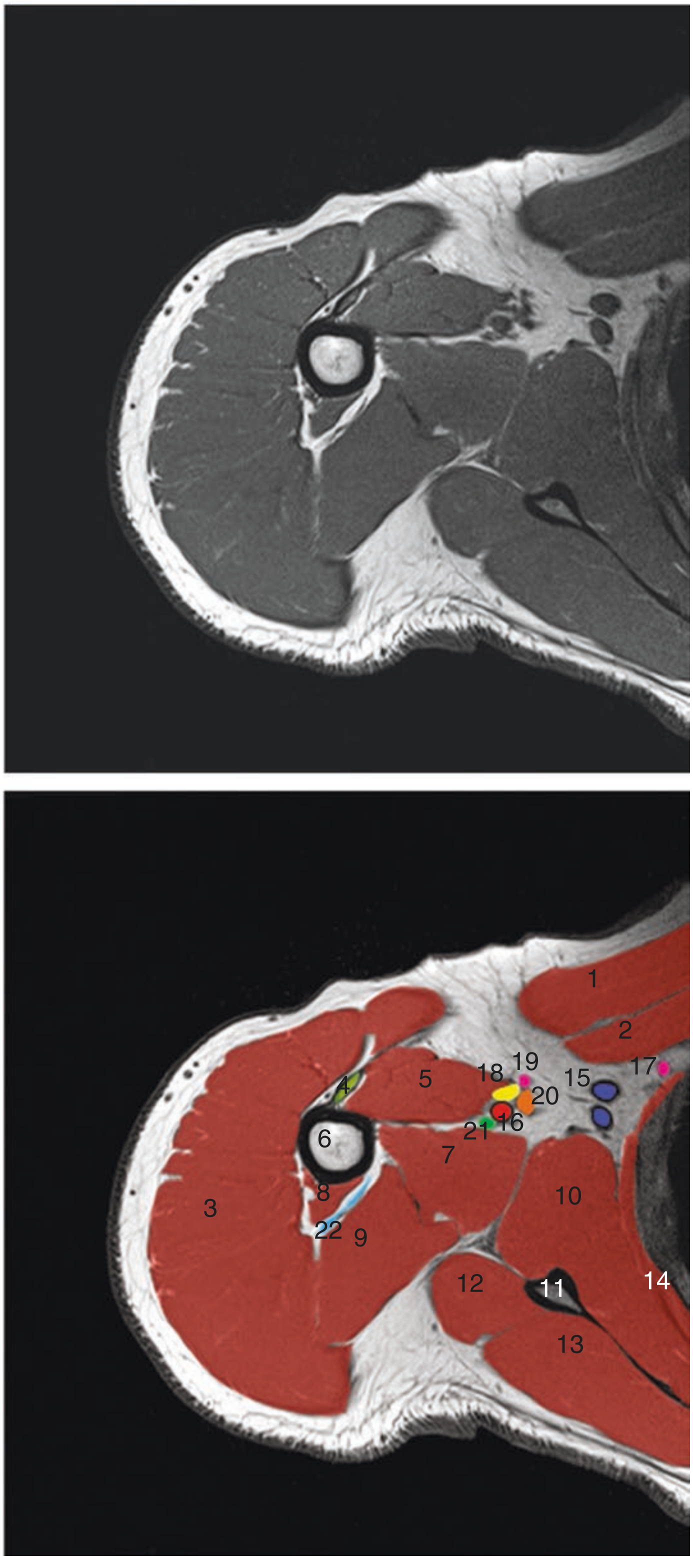
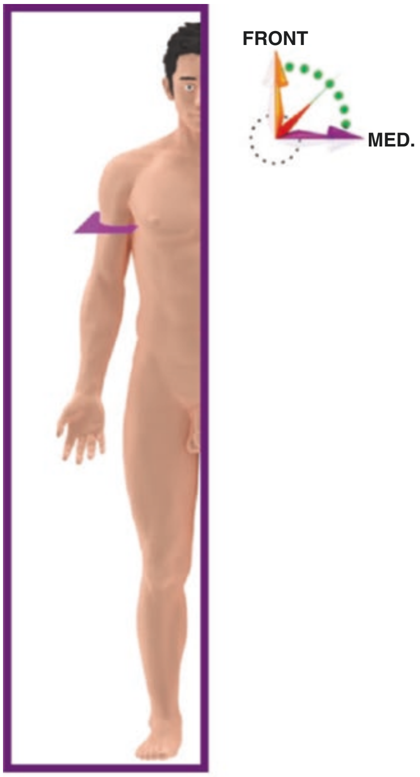
Figure MC10. Relations of the musculocutaneous nerve in the elbow and forearm, axial views.

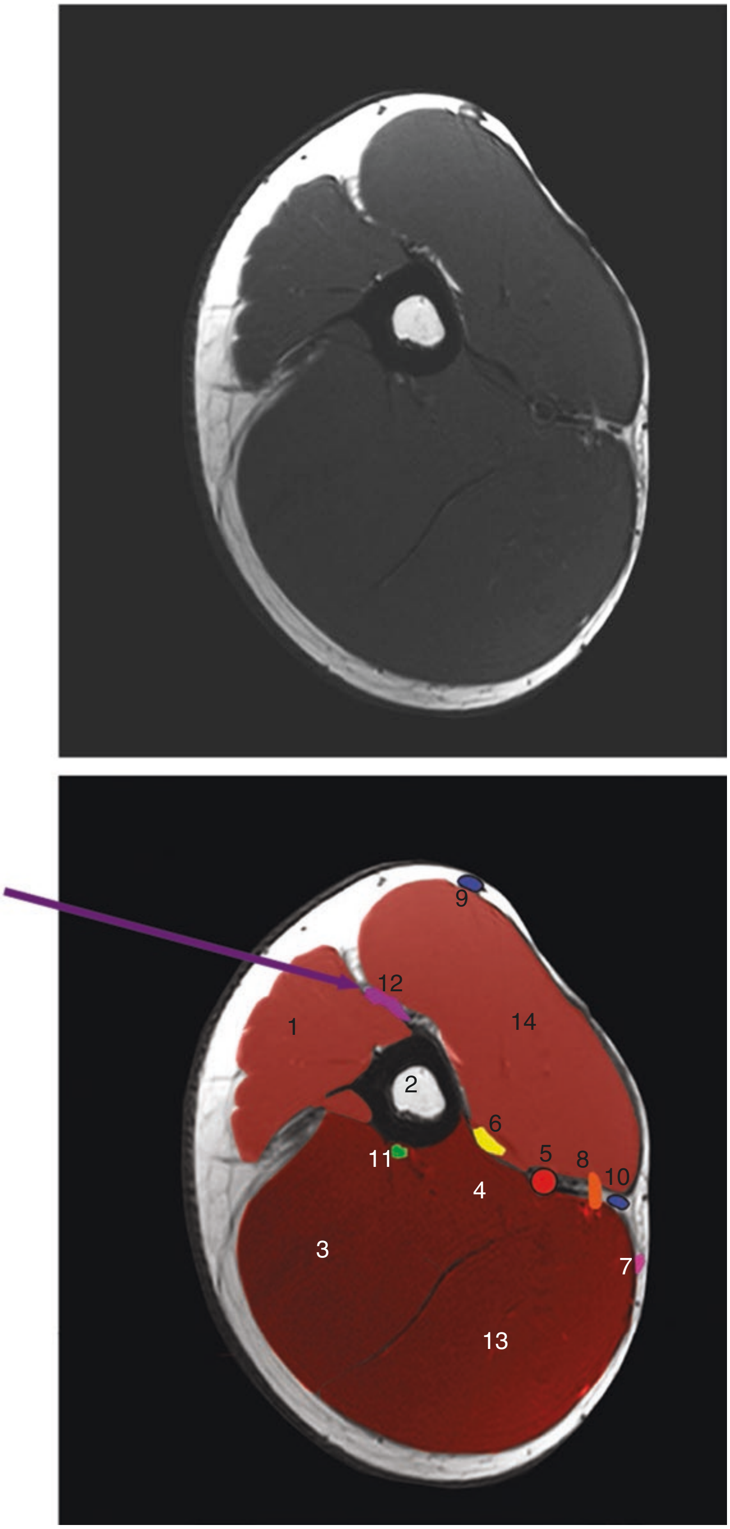




1- Pectoralis major muscle
2- Pectoralis minor muscle
3- Deltoid muscle
4- Long head of the biceps brachii muscle
5- Latissimus dorsi muscle
6- Humerus
7- Teres major muscle
8- Lateral head of the triceps brachii muscle
9- Medial head of the triceps brachii muscle
10- Subscapularis muscle
11- Scapula
12- Teres minor muscle
13- Infraspinatus muscle
14- Serratus anterior
15- Brachial vein
16- Brachial artery
17- Medial cutaneous nerve of arm
18- Median nerve
19- Medial cutaneous nerve of forearm
20- Ulnar nerve
21- Radial nerve
22- Axillary nerve

Figure MC11. MRI scans in the shoulder through the musculocutaneous nerve.





1- Deltoid muscle

2- Humerus

3- Lateral head of the triceps brachii muscle

4- Medial head of the triceps brachii muscle

5- Brachial artery

6- Median nerve

7- Medial cutaneous nerve of forearm

8- Ulnar nerve

9- Cephalic vein

10- Basilic vein

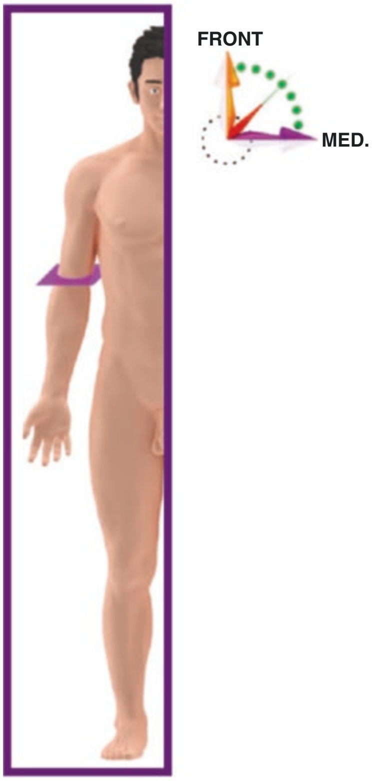
11- Radial nerve

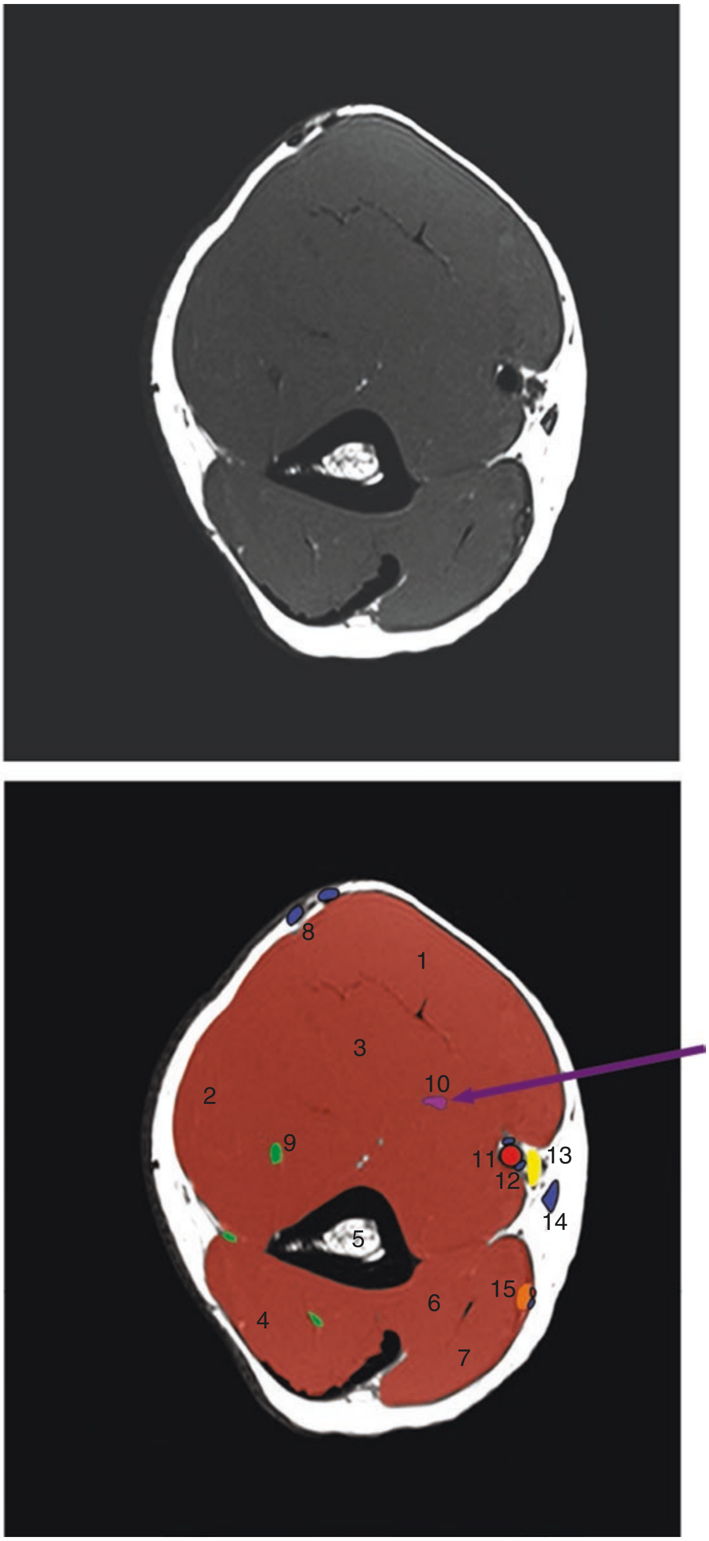
12- Musculocutaneous nerve

13- Long head of the triceps brachii muscle

14- Biceps brachii muscle

Figure MC12. MRI scans at the proximal third of the arm through the musculocutaneous nerve.





1- Biceps brachii muscle

2- Brachioradialis muscle

3- Brachialis muscle

4- Lateral head of the triceps brachii muscle

5- Humerus

6- Long head of the triceps brachii muscle

7- Medial head of the triceps brachii muscle

8- Cephalic vein

9- Radial nerve

10- Musculocutaneous nerve

11- Brachial artery

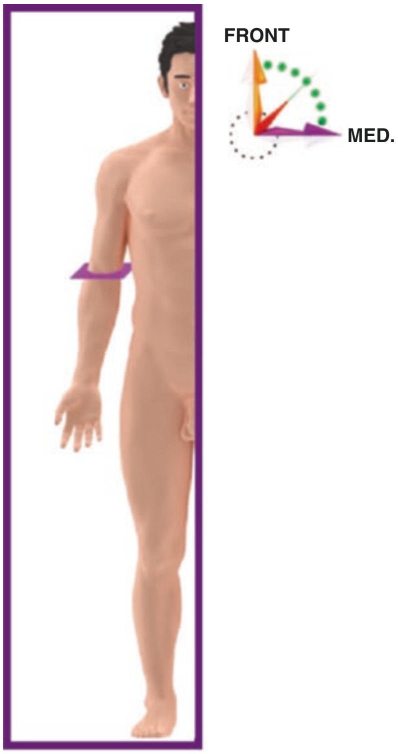
12- Brachial vein

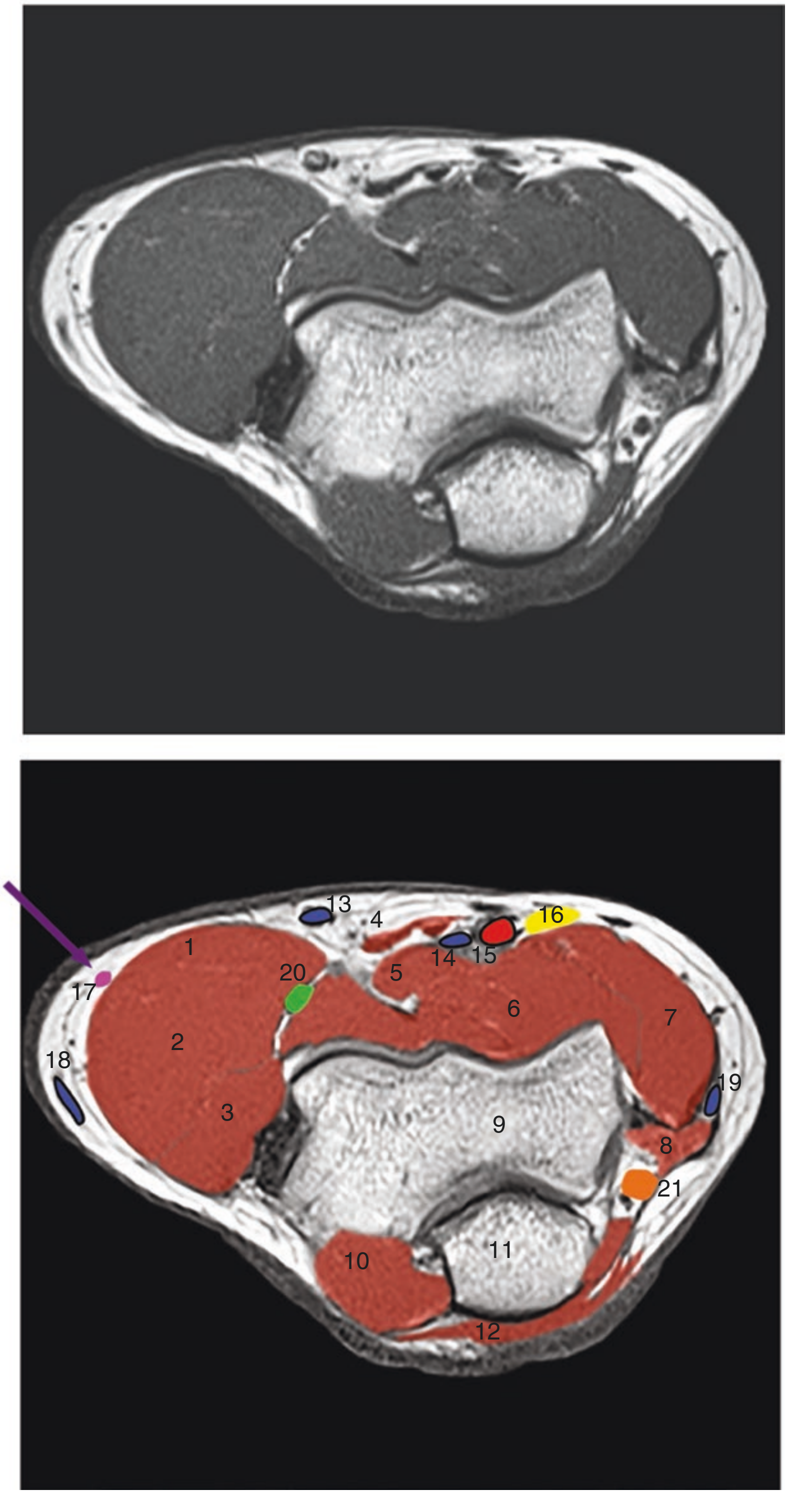
13- Median nerve

14- Basilic vein

15- Ulnar nerve

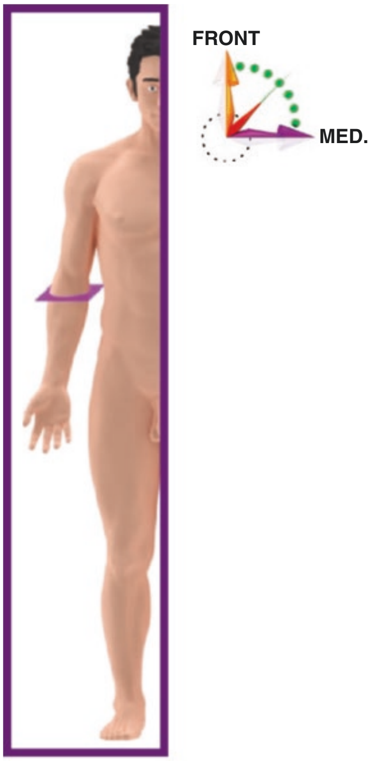
Figure MC13. MRI scans at the distal third of the arm through the musculocutaneous nerve.

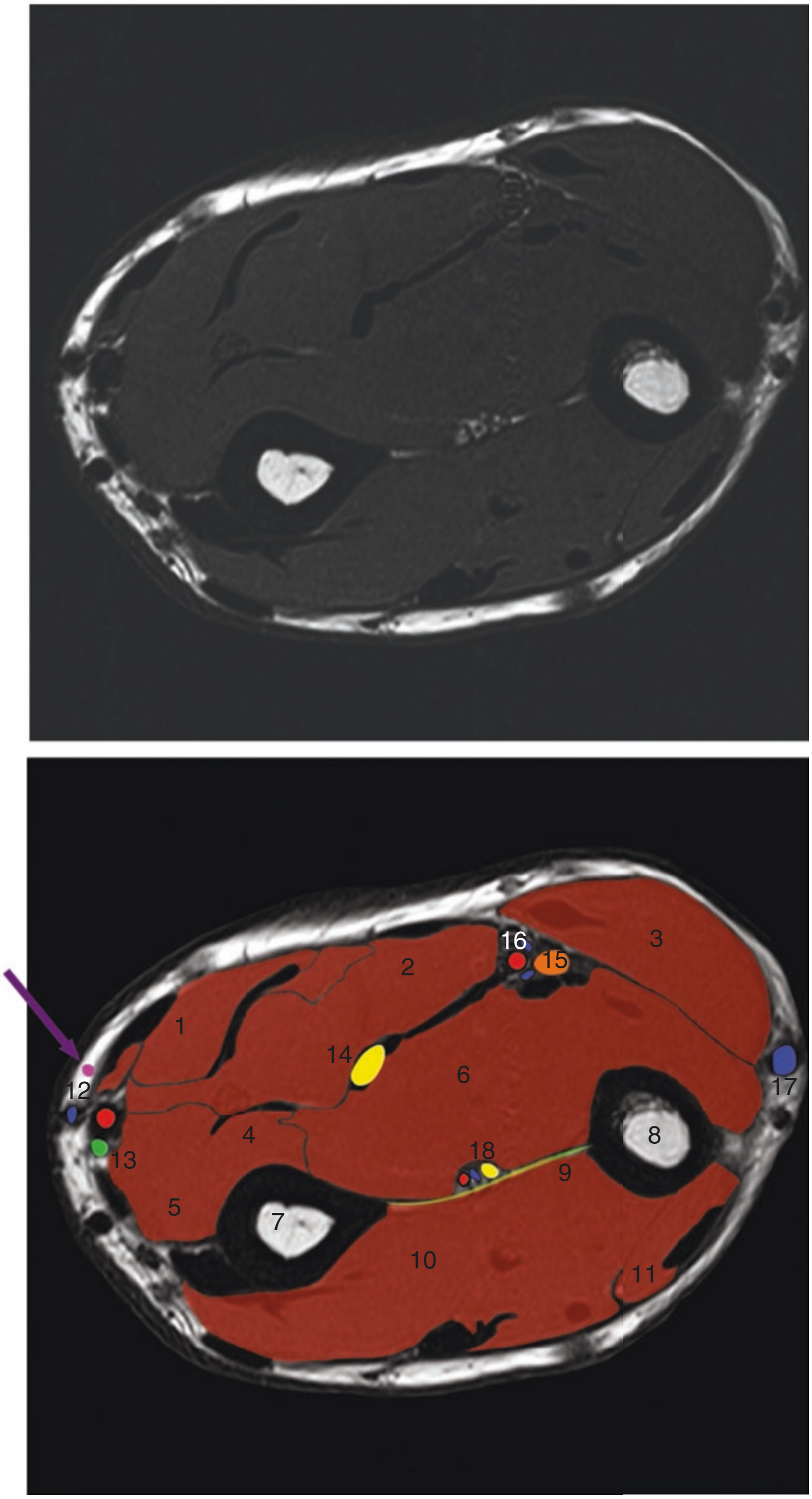




1- Brachioradialis muscle
2- Extensor carpi radialis longus muscle
3- Extensor carpi radialis brevis muscle
4- Biceps brachii muscle
5- Tendon of the long head of biceps
6- Brachialis muscle
7- Pronator teres muscle
8- Tendon of the median epycondylian muscles
9- Humerus
10- Anconeus muscle
11- Ulna
12- Triceps brachii muscle
13- Medial vein at the elbow
14- Brachial vein
15- Brachial artery
16- Median nerve
17- Musculocutaneous nerve
18- Cephalic vein
19- Basilic vein
20- Radial nerve
21- Ulnar nerve

Figure MC14. MRI scans in the elbow through the musculocutaneous nerve.





1- Flexor carpi radialis muscle

2- Flexor digitorum superficialis muscle

3- Flexor carpi ulnaris muscle

4- Flexor pollicis longus muscle

5- Extensor carpi radialis brevis muscle

6- Flexor digitorum profundus muscle

7- Radius

8- Ulna

9- Interosseous membrane of the forearm

10- Posterior compartment of the extensor digitorum muscles

11- Extensor carpi muscle

12- Radial artery and vein

13- Radial nerve

14- Median nerve

15- Ulnar nerve

16- Ulnar artery and vein

17- Basilic vein

18- Anterior interosseous artery, vein and nerve

Figure MC15. MRI scans in the forearm through the musculocutaneous nerve.

Pathology

Isolated injuries of the musculocutaneous nerve are less frequent than those of other mixed nerves of the upper limb (Figure MC16).

Aetiology

- Traction: This can happen when one makes a brutal abduction movement and a lateral rotation of the arm, but it is not the main injury mechanism of the musculocutaneous nerve. If the injury is not brutal, the incriminated mechanism is more likely a disruption of the nerve's vascularization rather than a direct injury.
- Division: This is generally postsurgical, or spontaneous in very rare cases.
- Compression: The musculocutaneous nerve can mainly be compressed at the level of two potential spots: the crossing point of the coracobrachialis muscle, at a distance equivalent to four times the width of a finger under the tip of the coracoid process, during a movement of brutal retropulsion of the scapula, and at the level of the elbow pit by the aponeurosis and the tendon of the biceps against the biceps brachii's fascia. This compression can also happen in the case of repeated and/or unusual efforts causing an abnormally intense contraction of the muscles in the upper part of the limb (mainly the biceps brachii, brachialis and coracobrachialis). If the injury is remote enough, it only affects the sensitive function of the nerve, the lateral cutaneous nerve of the forearm (as a reminder, the musculocutaneous nerve becomes the lateral cutaneous nerve of the forearm at the level of the lateral epicondyle of the humerus).

Clinical Signs

- Sensitive signs: Hypoesthesia, neuropathic pain and/or paraesthesia concern the sensitive territory of the musculocutaneous nerve—the forearm's lateral face up to the thumb.
- Motor signs: The problem felt by the patient generally relates to a hypotonia of the biceps brachii. The motor dysfunction concerns the flexion of the forearm on the arm, especially when the arm is placed in a position of supination. When the injury is chronic, we can observe a global disuse atrophy of the muscles of the upper part of the limb. The bicipital reflex is not triggered anymore (C5), except in the case of an isolated injury of the lateral cutaneous nerve of the forearm.

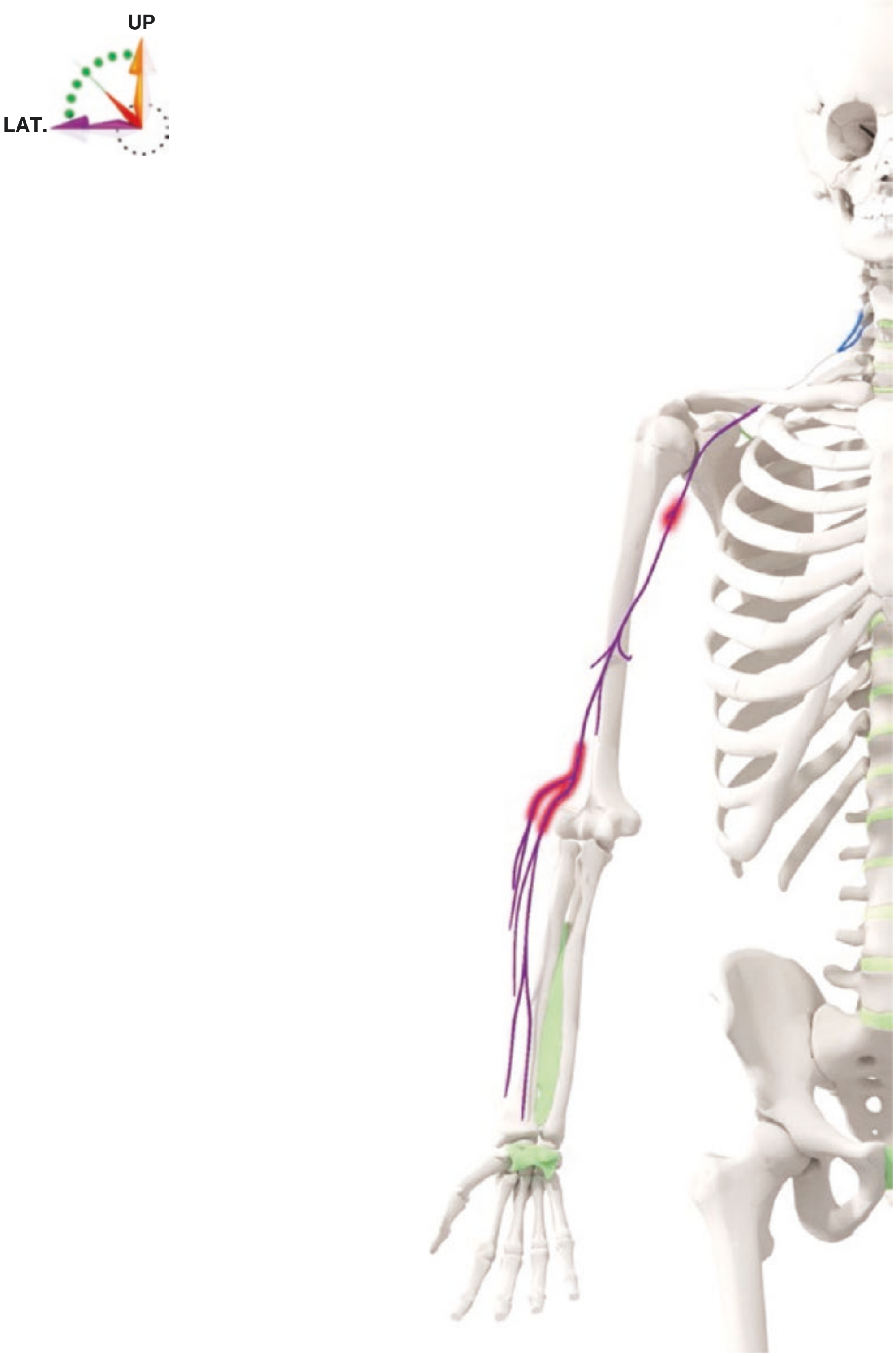
Explorations

- An electroneuromyography allows the isolation of an axonal and/or demyelinating of the musculocutaneous nerve. First and foremost, it assesses the innervation of the biceps brachii muscle.

No other complementary examination is necessary in the case of clear clinical context.

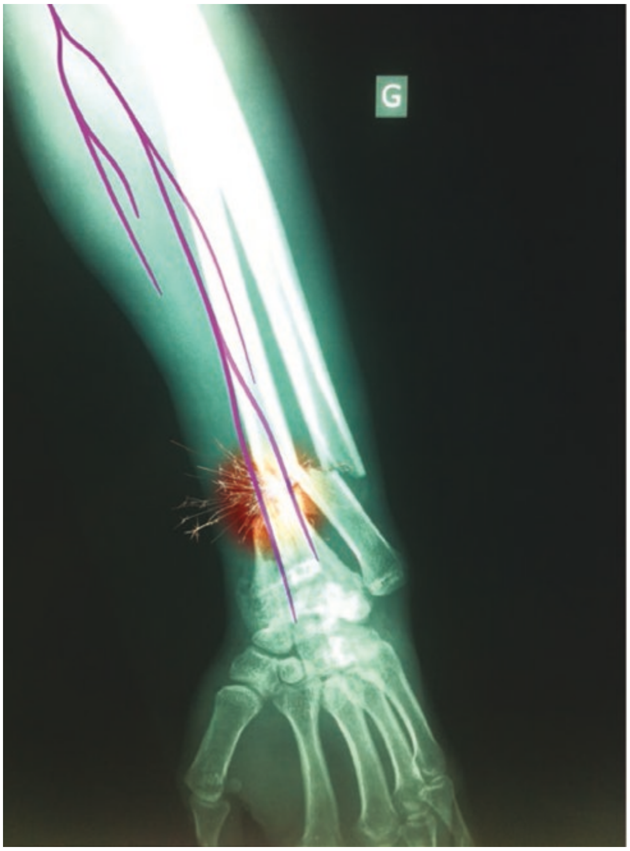
Treatment

First-line treatment is analgesic and conservative. A surgical decompression will only be necessary if the conservative treatment remained unsuccessful after more than 3 months of follow-up.

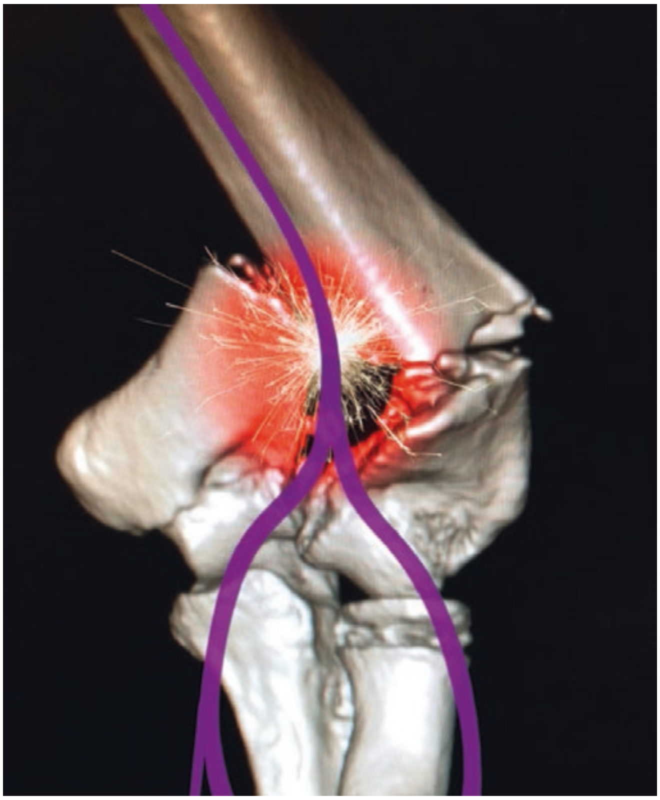


Most common injury area of the musculocutaneous nerve.

Figure MC16. Pathology of the musculocutaneous nerve.



a. Injury of the anterior branch of the musculocutaneous nerve after a fracture of the forearm's bone. From a clinical point of view, a hypoesthesia on the anterolateral face of the forearm can be observed.



b. Injury of the sensitive branches of the musculocutaneous nerve after a complex fracture of the distal extremity of the humerus.

Figure MC17. (**a**) Injury of the anterior branch of the musculocutaneous nerve after a fracture of the forearm bone. From a clinical point of view, a hypoesthesia on the anterolateral. (**b**) Injury of the sensitive branches of the musculocutaneous nerve after a complex fracture of the distal extremity of the humerus.

Morphological Data: Sono Anatomy

It stems from the lateral bundle of the brachial plexus, perforates the coracobrachialis muscle and travels between the biceps brachii muscle in front and the brachialis muscle in the dorsal. It emerges at the lower part of the arm by perforating the brachioradialis and biceps brachii muscles at the lateral bicipital groove and thereby becomes the lateral cutaneous nerve of the forearm.

Installation

The patient is in supine position, the arm in 90° abduction and the hand in supination or neutral position.

Equipment and Location

- Type of probe: surface linear from 5 to 13 MHz
- Probe axis: para-sagittal

The skin marker is the distal part of the axillary cavity.

Ultrasound Procedure

The structures to be identified are all above vascular: artery and brachial vein, and correspond also to the latissimus dorsi muscle. The probe is more anterior on the para-sagittal plane, the musculocutaneous nerve is in an anterolateral position, in contact with the coracobrachialis muscle and the tendon of the latissimus dorsi muscle.

By performing a translational movement from proximal to distal, it will be discovered more distally in contact with the coracobrachialis muscle and the tendon of the short head of the biceps brachii muscle.

Finally, it can be discovered when perforated on either side of the coracobrachialis muscle.

There are many anatomical variations and anastomoses with median (most frequent), radial and ulnar nerves.

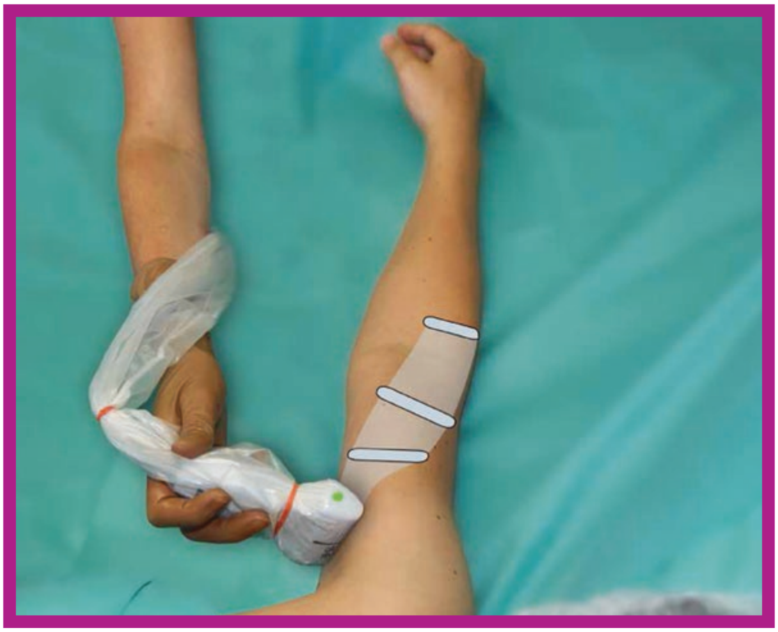
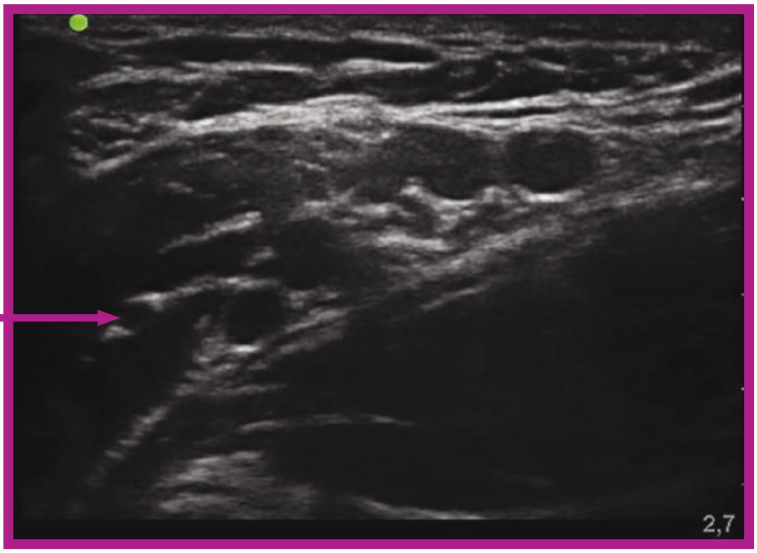
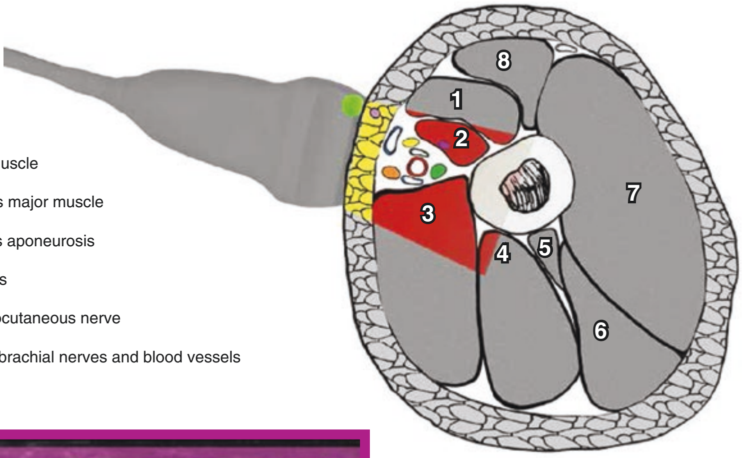
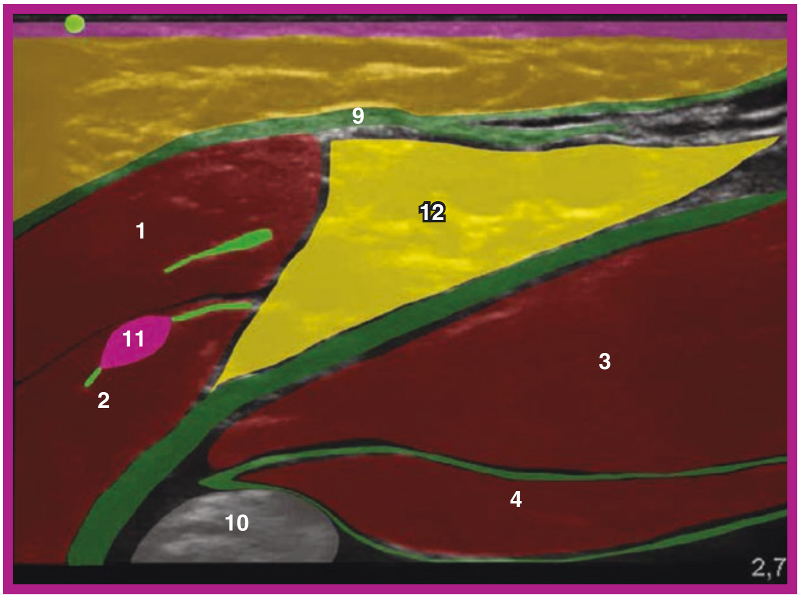


Figure MC18. An overview of ultrasound positions to identify the musculocutaneous nerve at the arm level.





1- Biceps brachii muscle
2- Coracobrachialis muscle
3- Latissimus dorsi muscle
4- Teres major muscle
5- Long head of the triceps brachii muscle
6- Lateral head of the triceps brachii muscle
7- Deltoid muscle
8- Pectoralis major muscle
9- Brachialis aponeurosis
10- Humerus
11- Musculocutaneous nerve
12- Axillary brachial nerves and blood vessels



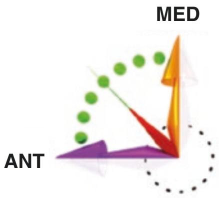
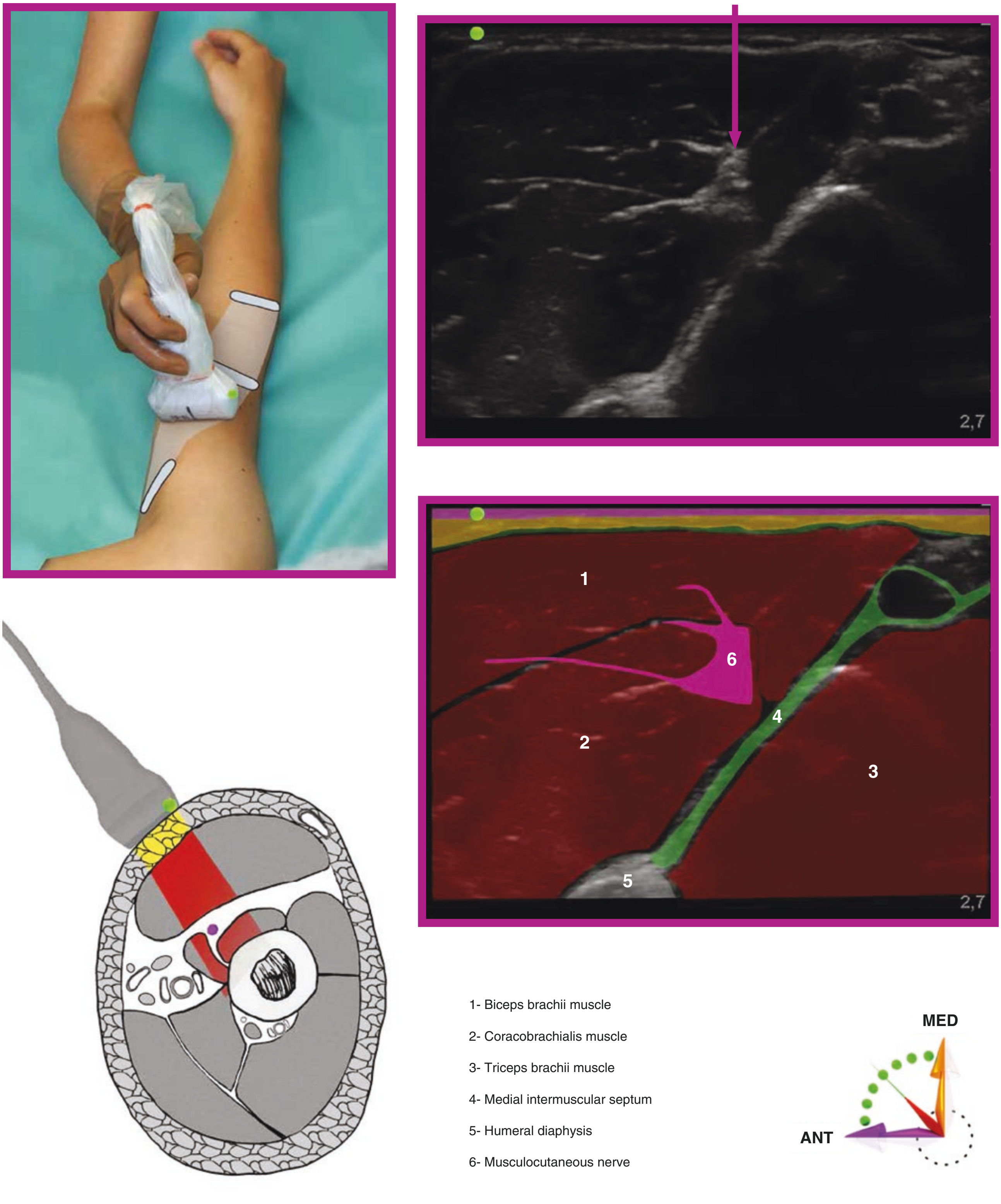
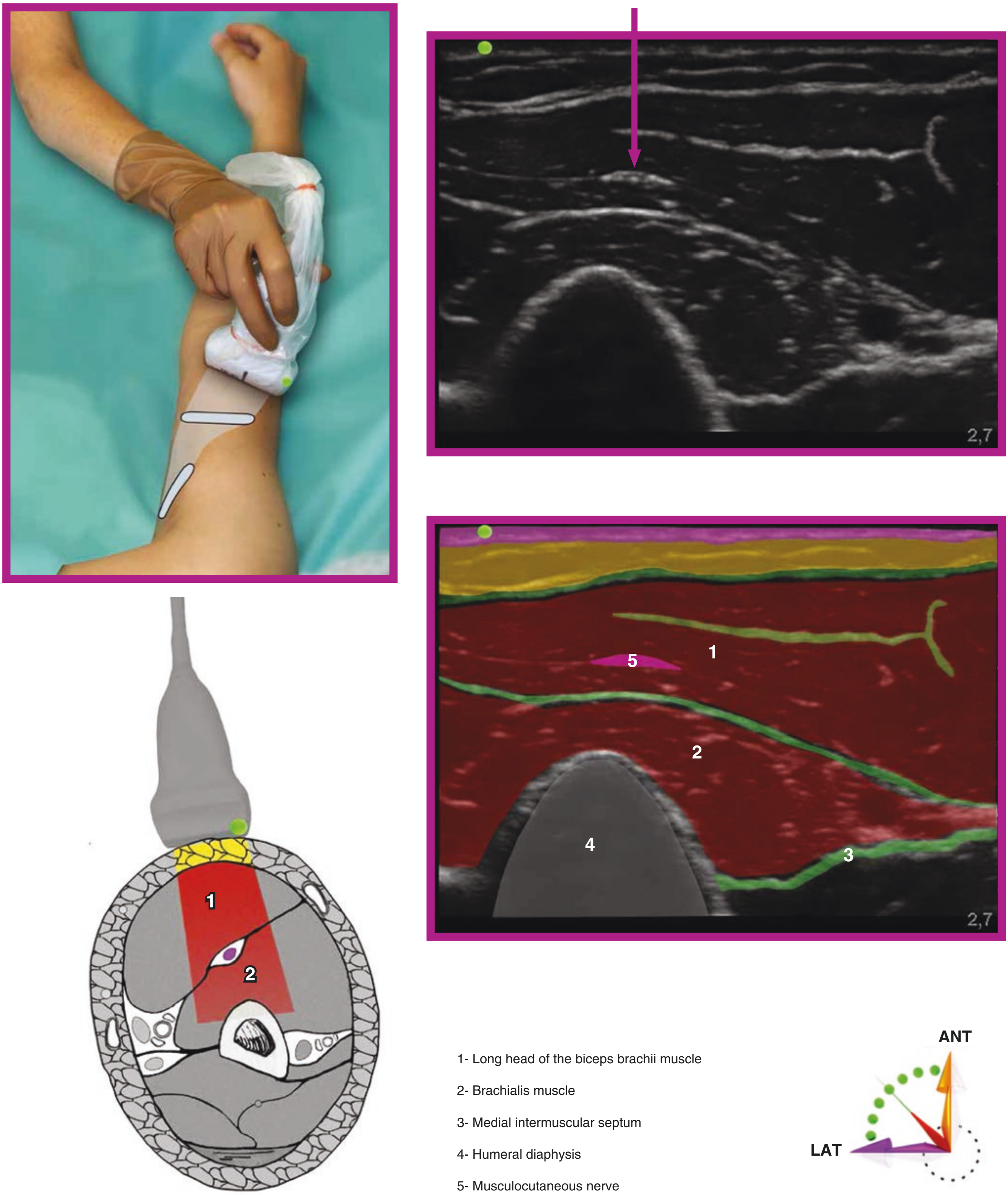


Figure MC19. Ultrasound transversal views of the musculocutaneous nerve at the distal part of the axillary pit.



1- Biceps brachii muscle
2- Coracobrachialis muscle
3- Triceps brachii muscle
4- Medial intermuscular septum
5- Humeral diaphysis
6- Musculocutaneous nerve

Figure MC20. Ultrasound transversal views of the musculocutaneous nerve at the proximal third of the arm, showing coracobrachialis muscle crossed by the musculocutaneous nerve and its collateral division branches.



1- Long head of the biceps brachii muscle

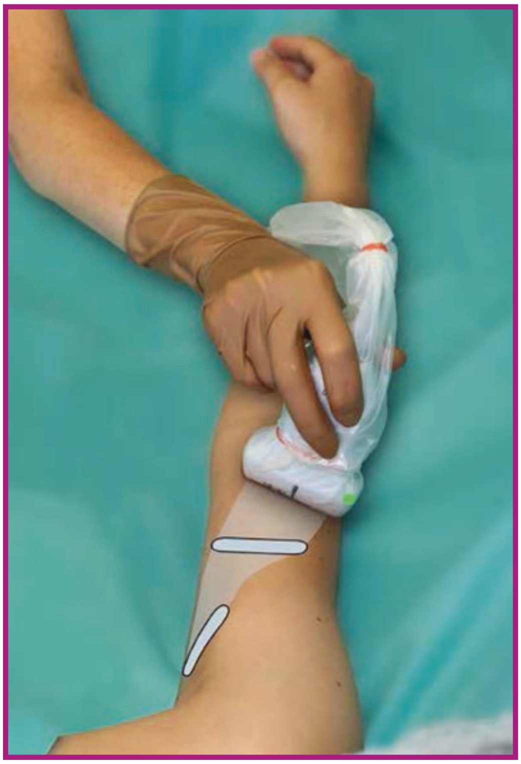
2- Brachialis muscle

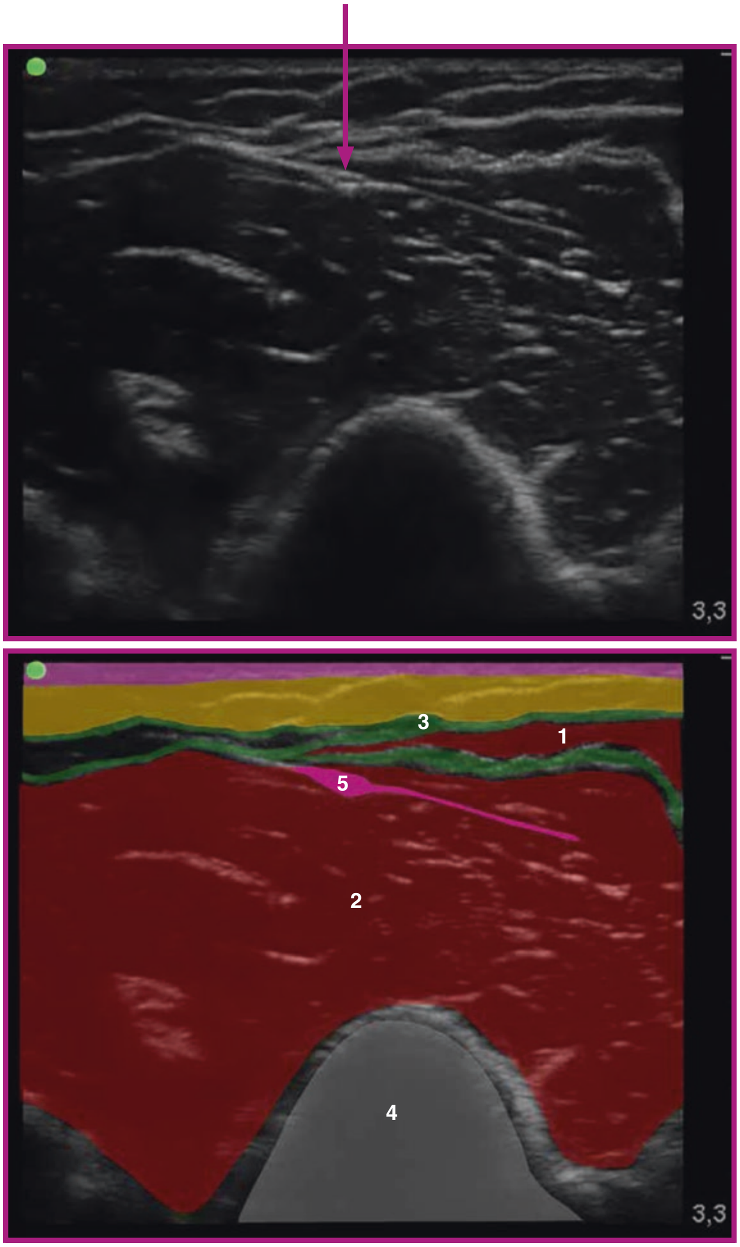
3- Medial intermuscular septum

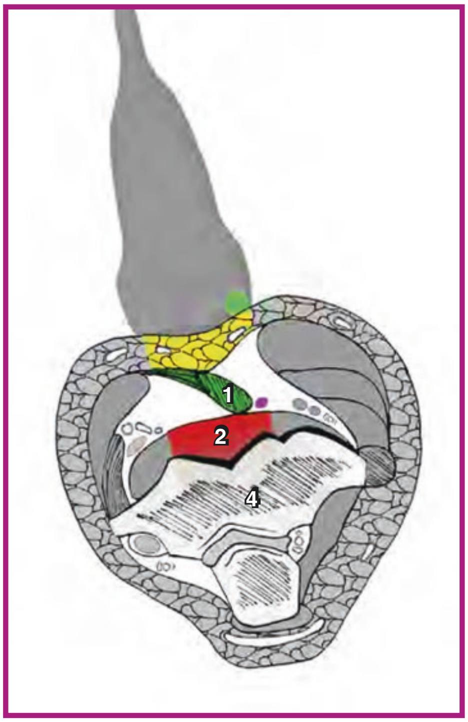
4- Humeral diaphysis

5- Musculocutaneous nerve

Figure MC21. Ultrasound transversal views at the middle tier—distal third of the arm.







1- Long head of the biceps brachii muscle

2- Brachialis muscle

3- Septum intermusculaire médial

4- Humeral diaphysis

5- Musculocutaneous nerve

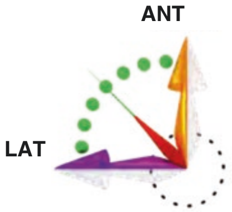
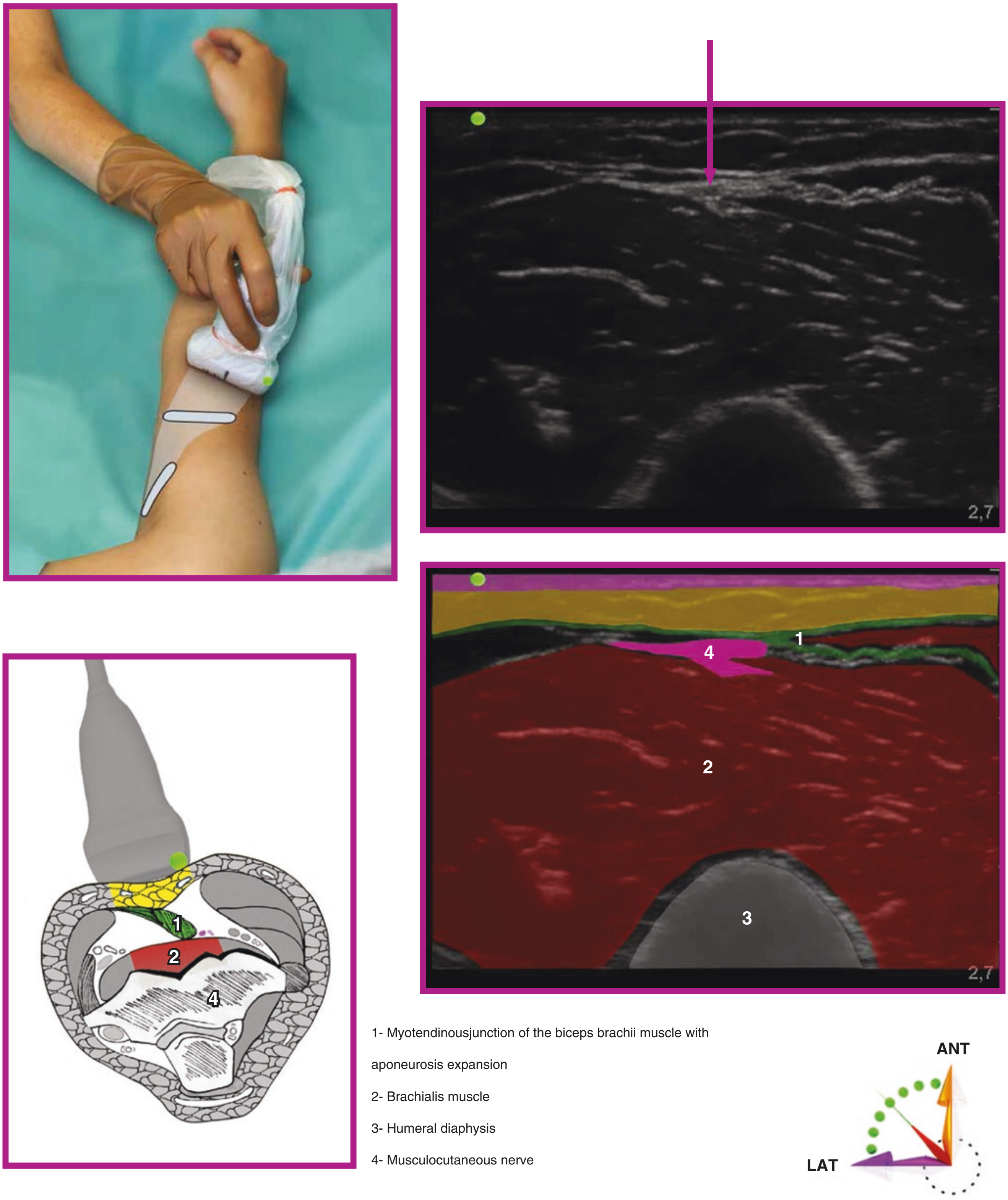


Figure MC22. Ultrasound transversal views at the distal third of the arm just above the bicipital groove.



1- Myotendinousjunction of the biceps brachii muscle with aponeurosis expansion

2- Brachialis muscle

3- Humeral diaphysis

4- Musculocutaneous nerve

Figure MC23. Ultrasound transversal views above the bicipital groove, just at the anterior and posterior division of the musculocutaneous nerve.

Interventional Procedure

Infiltration/Test Block

Indication

The anaesthesiological block of the musculocutaneous nerve can be used for analgesic purposes as part of analgesic management in pain clinics or as part of a multidisciplinary disability consultation in order to determine whether an upper limb is spastic or retracted at the elbow flexion level after a stroke.

Etiopathogenesis can be traumatic and also ductal, with 2 levels of sheathing: the first, at the level of its passage of the coracobrachialis muscle; the second, at the level of the elbow, during perforation of the fascia of the biceps brachii muscle. Ultrasound is discriminatory in both the cases.

In-Plane Technology

The procedure is performed in elevation and abduction with a limb at an angle exceeding 90°. Depending on the level of the block, from proximal to distal, the entry point and angle of attack of the needle will initially be very vertical, and the needle will be delivered as the nerve is followed towards its distal position with an increasingly horizontal angle, pointing outwards. It should be kept in mind that in its proximal part, the nerve remains relatively superficial.

For greater accuracy, the operator can place the probe and the fifth ray of his hand on the junction of the deltoid and biceps brachii muscles. As the distal nerve is monitored, a sensory electrostimulation test will be valuable in case of doubt.

The advantage of this technique is that it provides superficial, especially proximal access to the nerve.

In this context, there is no particular interest in the out-of-plane technique due to the lack of visibility of the needle, especially in the proximal area. This technique may in the future assume a legitimate place in the distal area.

The choice of the block site depends on the clinical outcome:

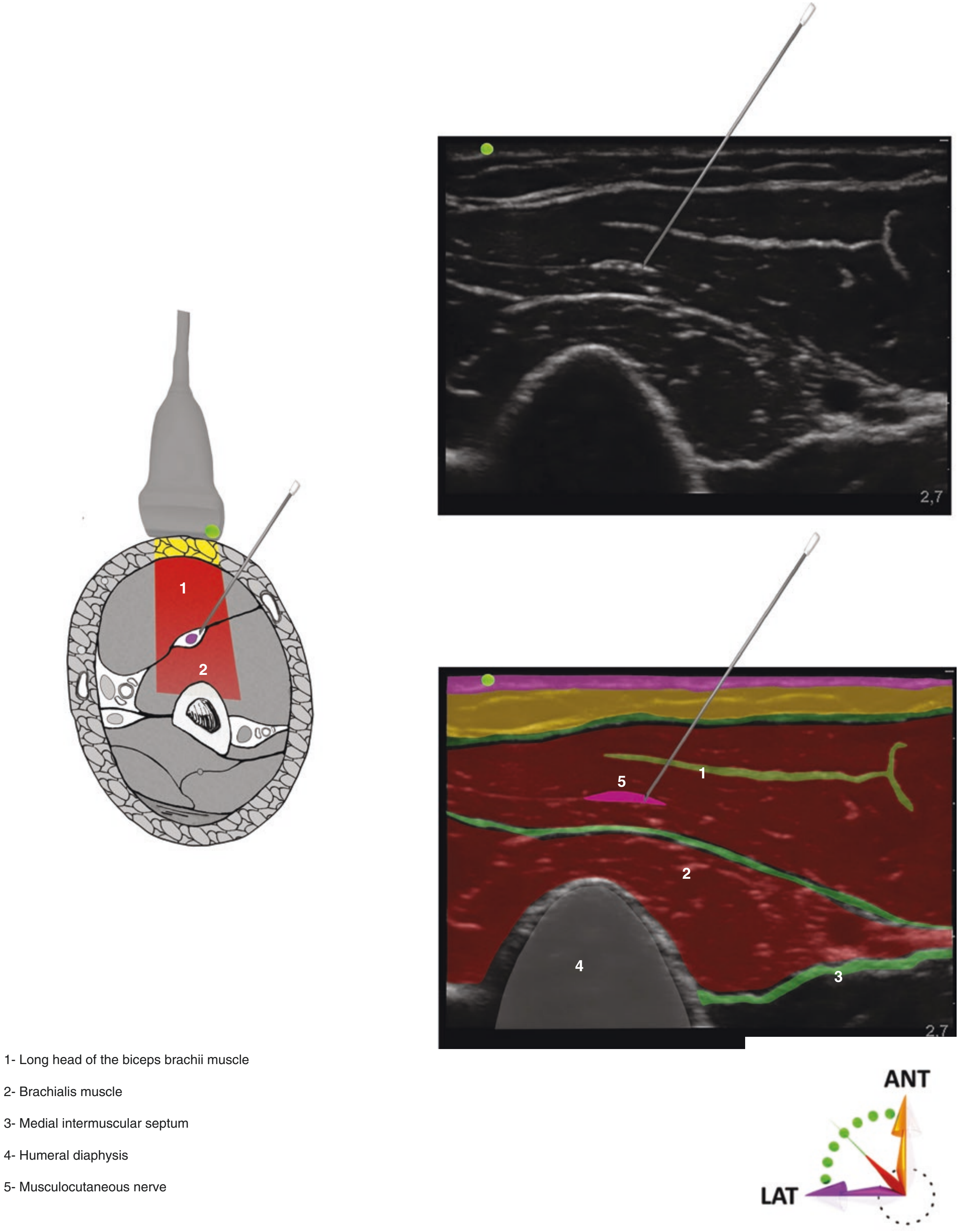
- If there is a suspicion of nerve compression by a ductal syndrome in the coracobrachialis muscle, there will be some proximal pain with a fairly high trigger zone, and the block will be performed at the junction of the upper and middle thirds of the arm.
- On the other hand, if the patient's medical history and profession expose him or her to repeated flexion-extension movements and if the pain is localized more in the elbow or the tendon of the biceps brachii muscle, a more distal block is preferred, approaching the distal third of the arm or elbow.

  If this block is for diagnostic purposes, a small injection volume (<1 cc) will be used to be perfectly selective while a hydrodissection can be performed to "drown" the nerve if the purpose of the block is essentially therapeutic.

Peripheral Nerve Stimulation (PNS)

The PNS of the proximal part of this nerve is difficult to achieve given the risks of mobilization of the material, given the repeated movements in this region. However, in case of proximal involvement, neurostimulation is possible by stimulating the brachial plexus of the C5–C6 roots.

PNS of the distal part of the nerve is possible just above the elbow under the fascia of the biceps brachii muscle.



1- Long head of the biceps brachii muscle

2- Brachialis muscle

3- Medial intermuscular septum

4- Humeral diaphysis

5- Musculocutaneous nerve

Figure MC24. Musculocutaneous nerve anaesthetic block (in plane technique).

Surgical Procedure

Surgical Indications

Musculocutaneous nerve surgery may be indicated in the following cases:

- Nerve repair after direct or indirect nerve trauma. It is a particularly violent retropulsion of the shoulder that is likely to damage this nerve with regard to the deltopectoral groove. Injury to the musculocutaneous nerve is responsible for visible paralysis of the biceps brachii and brachialis muscles. Associated with this is a sensory deficit located opposite the lateral face of the arm.
- Neurotomy procedure to treat refractory spasticity of the elbow in flexion is recommended following damage to the central nervous system, in the event of partial but transient efficacy of botulinum toxin injections.

Surgical Approaches

Skin Incision

The abduction of the arm, at best at 90°, allows an approach to this nerve through an incision starting approximately in the middle of the segment connecting the coracoid process and the top of the armpit hollow at the top. It extends along the anterior axillary line to bend at the axillary fold and descends along the inner surface of the arm, facing the coracobrachialis muscle and then the humeral canal. Installation of surgical fields should allow for the evaluation of muscle responses to electrical stimulation when dissection is difficult.

Nervous Exposure

First, the VC is isolated at the deltopectoral groove, and then the cephalic vein is insinuated at its lateral edge to spread the deltoid muscle fibres out and the pectoralis major muscle in. The inner edge of the coracobrachialis muscle is then identified by incising the pectoral fascia, and the muscle is followed to approach the musculocutaneous nerve about three fingertips below its insertion on the coracoid process. It is at this level, in front of and outside the axillary artery, below the anterolateral trunk of the brachial plexus.

Under neurostimulation, we can isolate the motor fascicles of the sensitives that will constitute the future lateral cutaneous sensory nerve of the forearm. Once the motor shoots have been identified, it will be possible to individualize the branches for coracobrachialis, biceps brachii and the brachialis muscles a little lower.

Technical Pitfalls

- Vascular lesion of the axillary artery and then the brachial artery
- Direct nerve damage at the inner edge of the coracobrachialis muscle

It is difficult to identify and individualize its highly variable motor branches, but this is necessary in order to avoid a disappointing result following a neurotomy.

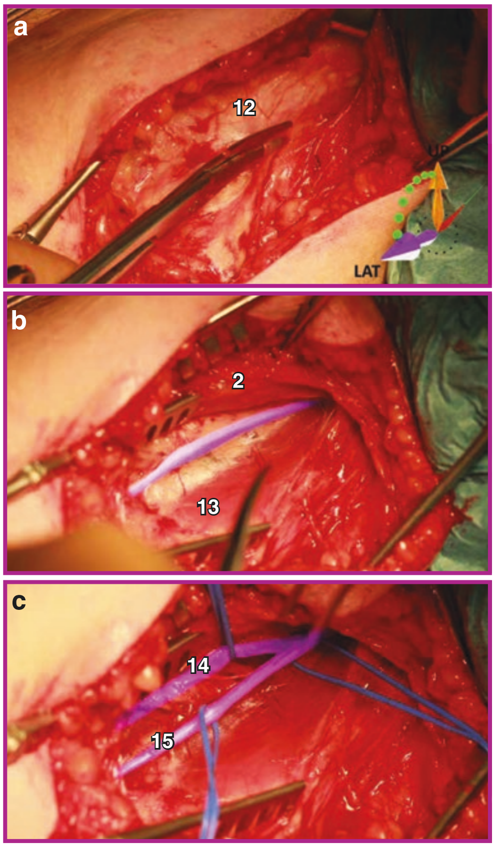
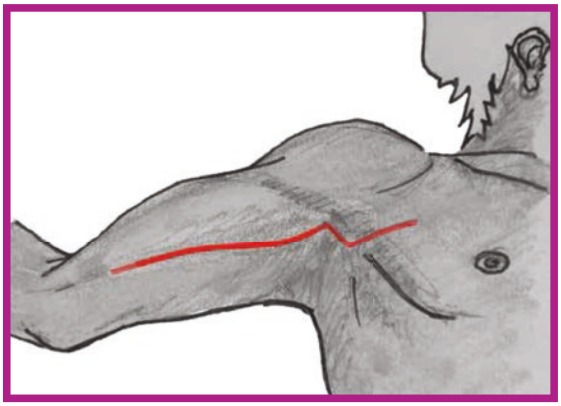


Figure MC25. Operative view of the musculocutaneous nerve. (**a**) Brachialis aponeurosis identification. (**b**) Nerve trunk identification. (**c**) Collateral branches exposure.



1- Axillary artery

2- Biceps brachii muscle

3- Medial cutaneous nerve of arm

4- Medial cutaneous nerve of forearm

5- Pectoralis major muscle

6- Brachialis artery

7- Coracobrachialis muscle

8- Ulnar nerve

9- Median nerve

10- Musculocutaneous nerve

11- Brachialis vein

12- Brachialis fascia

13- Brachialis muscle

14- Motor branches of the biceps brachii muscle

15- Lateral cutaneous nerve of forearm

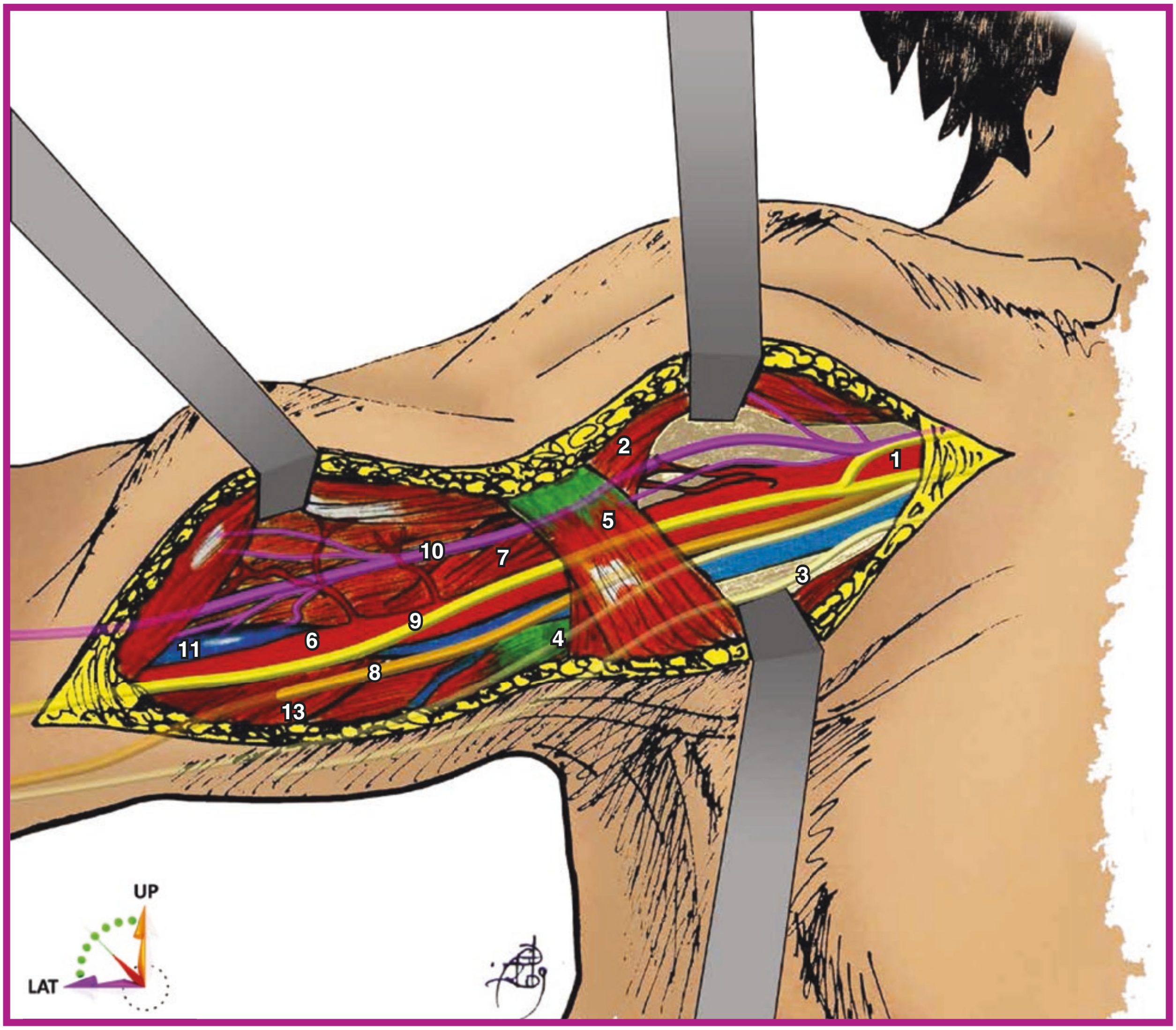


Figure MC26. Surgical approach of the musculocutaneous nerve at the arm level.

The Axillary Nerve

The Musculocutaneous Nerve

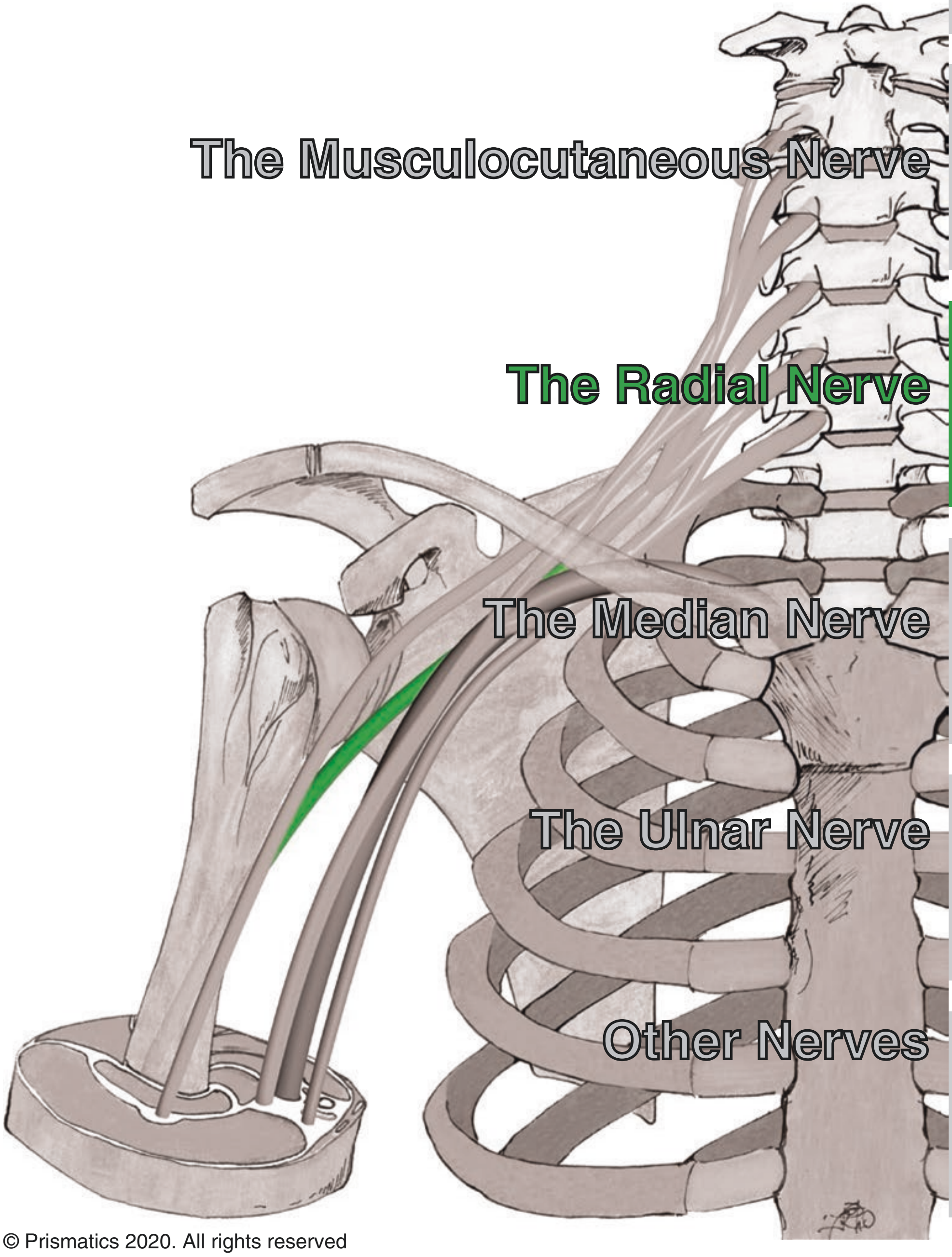
The Radial Nerve

The Median Nerve

The Ulnar Nerve

Other Nerves

R



The Radial Nerve

Morphological Data

The radial nerve corresponds to the most voluminous terminal branch of the brachial plexus. It receives branches from all three of the brachial plexus trunks (Figure R1).

Origin

The radial nerve constitutes nerve fibres coming from the C5, C6, C7, C8 and T1 roots (Figures R1 and R2). It forms the main terminal branch of the posterior bundle, which gave rise to the axillary nerve slightly above. It is situated at the level of the posterior bundle's origin, behind the axillary artery. At this point, the median nerve is found in front of the artery, and the musculocutaneous nerve is situated laterally. The radial nerve leans against the subscapularis muscle (Figure R3, Chapter "The Axillary Nerve"), then crosses, in order from top to bottom, the tendons of the latissimus dorsi and the teres major (Figures R3, R4 and R10).

Path

The radial nerve enters the posterior compartment of the arm going through the lower axillary space, accompanied by the brachial artery, between the long head of the triceps brachii and its lateral head. It obliquely crosses the posterior aspect of the humerus in a specific groove (Figures R2 and R11) whilst being under the lateral head of the triceps brachii (Figure R3). The insertions of the lateral and medial heads of the triceps brachii are above and below the humeral groove of the radial nerve, respectively.

This particularly sensitive area of the nerve corresponds to the most common nerve injury that occurs in diaphyseal fractures of the humerus (Figures R12 and R13).

At the end of this groove, it goes through the lateral intermuscular septum in order to penetrate the anterior compartment of the arm, between the brachioradialis muscle laterally and the brachialis medially (Figures R3, R8 and R12).

At the lateral epicondyle, the radial nerve is situated at the level of the lateral bicipital groove, in relation with the biceps brachialis and brachialis muscle medially and the brachioradialis muscle and the extensor carpi radialis longus laterally. At that level or several centimetres below, it divides into two terminal branches (Figures R3, R5 and R13).

Neurovascular Relations

At its origin, the radial nerve faces the axillary artery in front.

In the arm, it initially follows the path of the deep brachial artery and faces it laterally. At the midsection of the arm, it is crossed behind by the medial collateral artery, which is a branch of the profunda brachii artery. Then, the radial nerve follows the path of the radial collateral artery, which is a prolongation of the profunda brachii artery (Figure R4).

In the elbow, it faces the lateral epicondyle and the radial recurrent artery medially (Figure R6).

In the middle of the forearm, the superficial branch of the radial nerve joins the path of the radial artery that it faces

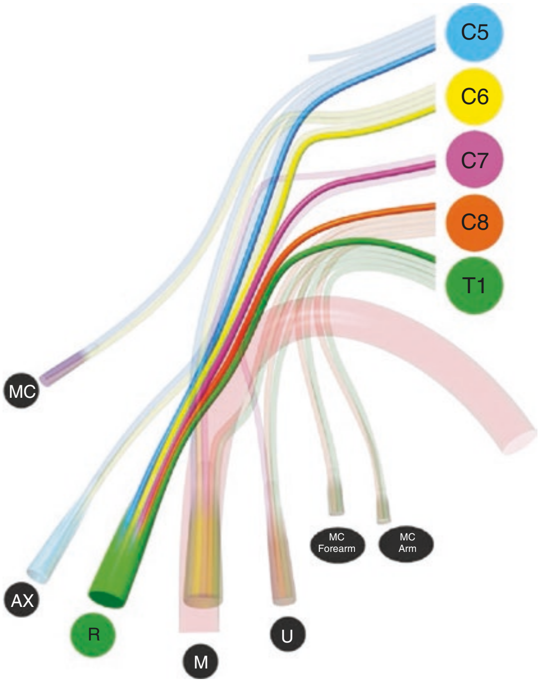


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Figure R1. Origin of the radial nerve.

Electronic Supplementary Material The online version of this chapter (https://doi.org/10.1007/978-3-030-49179-6_7) contains supplementary material, which is available to authorized users.

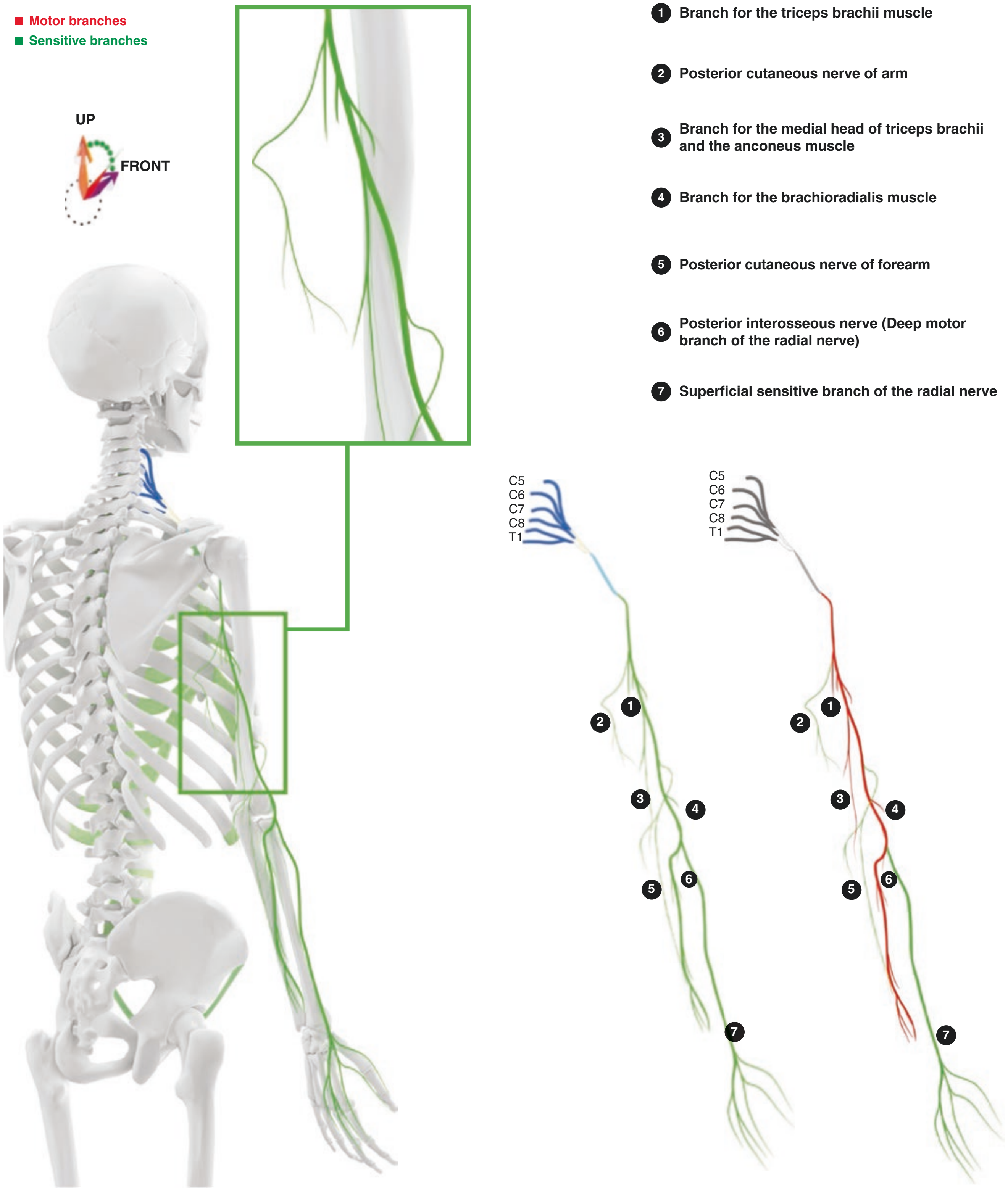
🟥 Motor branches
🟩 Sensitive branches
UP
FRONT
① Branch for the triceps brachii muscle
② Posterior cutaneous nerve of arm
③ Branch for the medial head of triceps brachii and the anconeus muscle
④ Branch for the brachioradialis muscle
⑤ Posterior cutaneous nerve of forearm
⑥ Posterior interosseous nerve (Deep motor branch of the radial nerve)
⑦ Superficial sensitive branch of the radial nerve
C5
C6
C7
C8
T1
1
2
3
4
5
6
7

Figure R2. Topographical distribution of the radial nerve and its relations with bones.

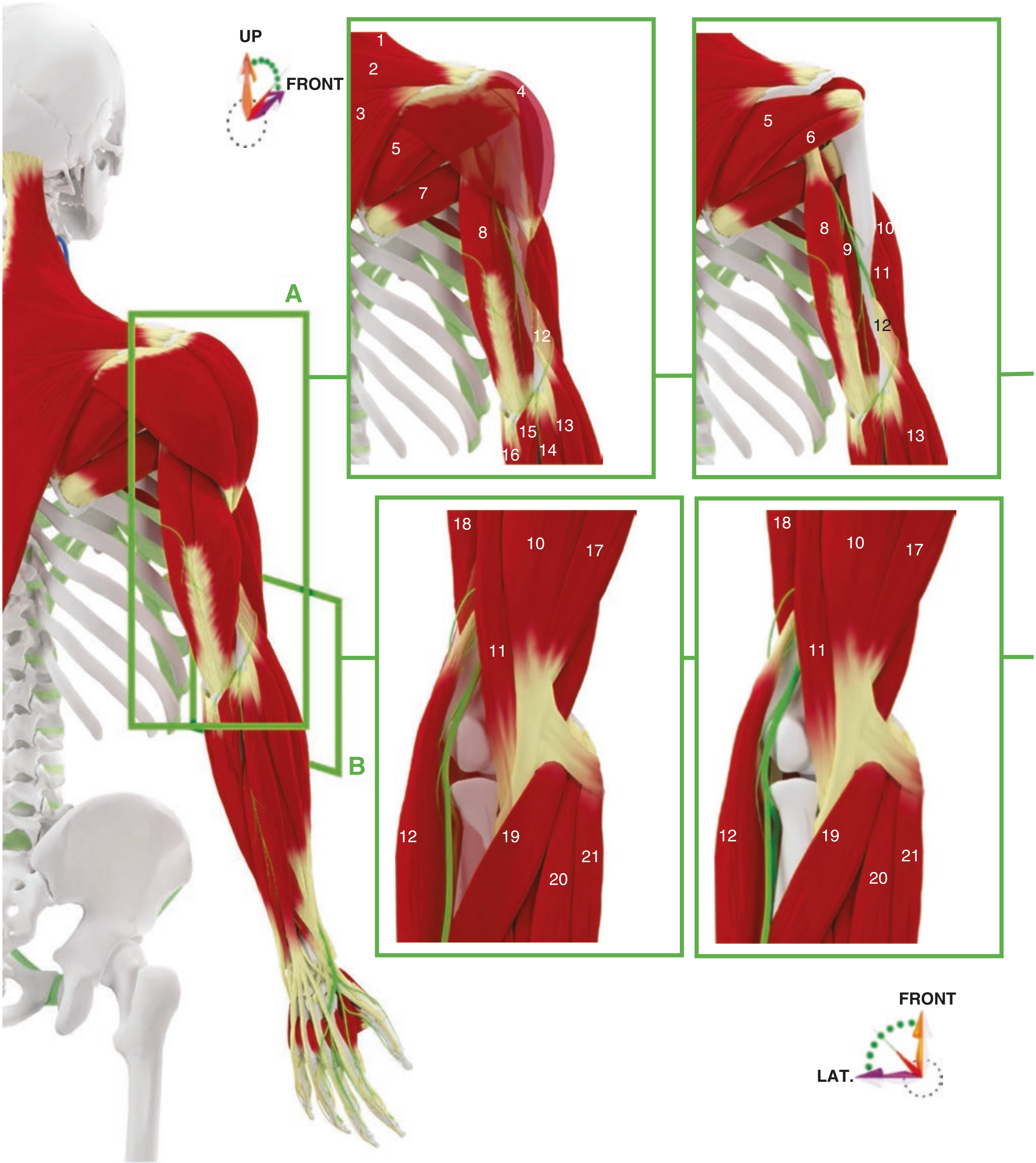
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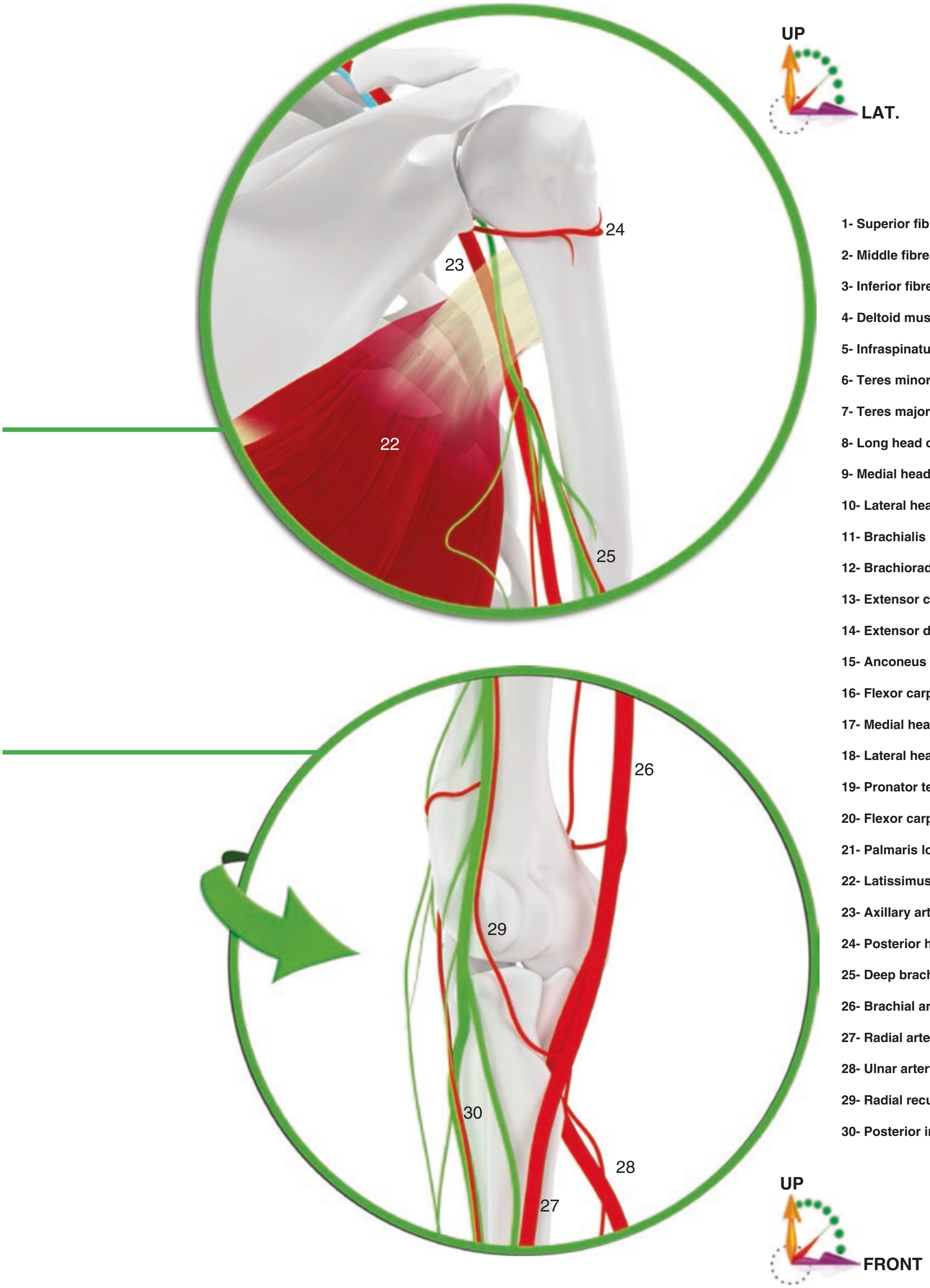
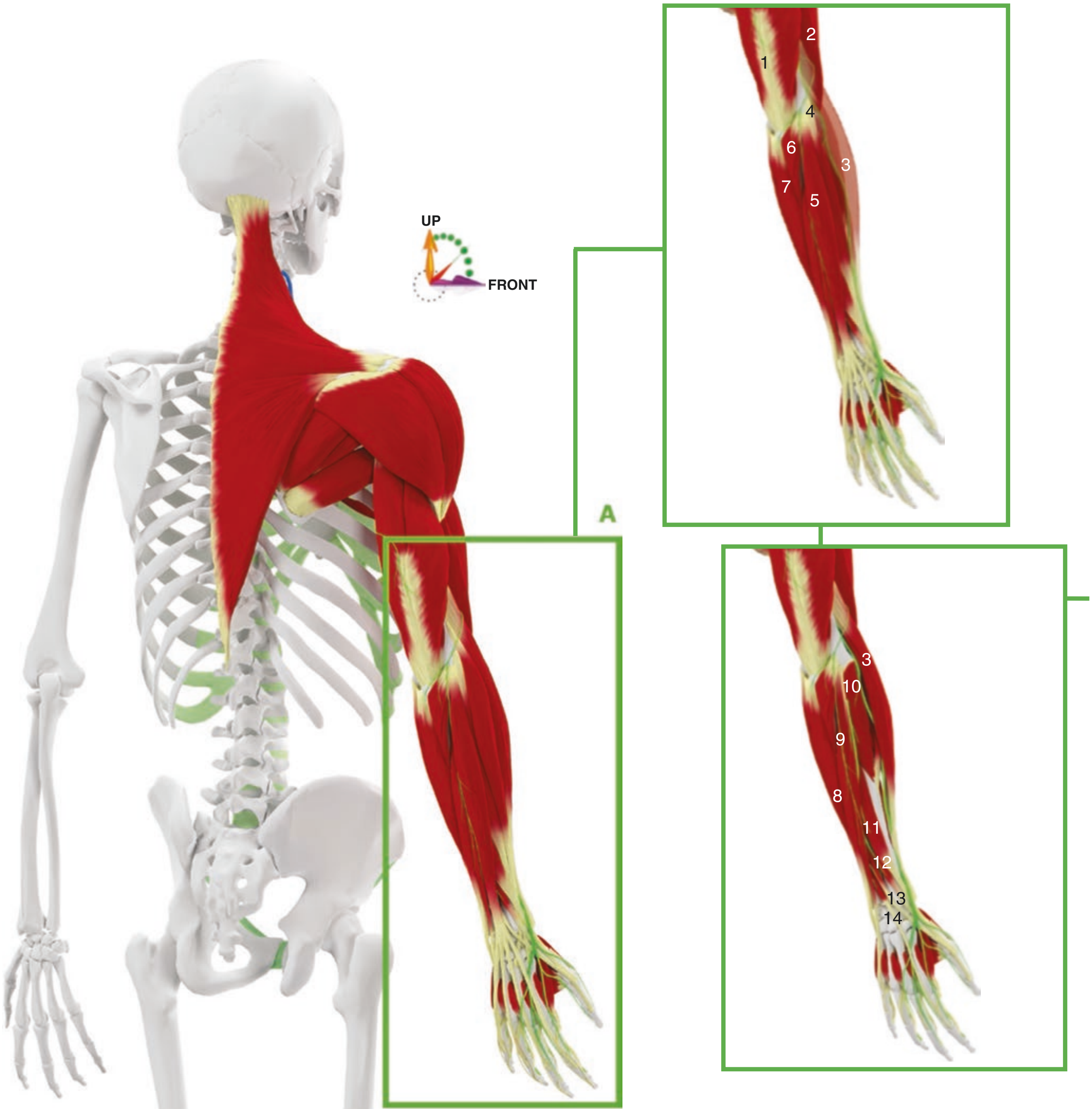
Figure R3. Path and relations of the radial nerve in the arm and elbow.



1- Superior fibres of the trapezius muscle
2- Middle fibres of the trapezius muscle
3- Inferior fibres of the trapezius muscle
4- Deltoid muscle
5- Infraspinatus muscle
6- Teres minor muscle
7- Teres major muscle
8- Long head of the triceps brachii muscle
9- Medial head of the triceps brachii muscle
10- Lateral head of the biceps brachii muscle
11- Brachialis muscle
12- Brachioradialis muscle
13- Extensor carpi radialis longus muscle
14- Extensor digitorum muscle
15- Anconeus muscle
16- Flexor carpi ulnaris muscle
17- Medial head of the biceps brachii muscle
18- Lateral head of the triceps brachii muscle
19- Pronator teres muscle
20- Flexor carpi radialis muscle
21- Palmaris longus muscle
22- Latissimus dorsi muscle
23- Axillary artery
24- Posterior humeral circumflex artery
25- Deep brachial artery
26- Brachial artery
27- Radial artery
28- Ulnar artery
29- Radial recurrent artery
30- Posterior interosseous artery

Figure R4. Vascular relations of the radial nerve in the arm and elbow.


UP
FRONT
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13
14

Figure R5. Path and relations of the radial nerve and its terminal branches in the forearm.

1- Triceps brachii muscle
2- Brachialis muscle
3- Brachioradialis muscle
4- Extensor carpi radialis brevis muscle
5- Extensor digitorum muscle
6- Anconeus muscle
7- Flexor carpi ulnaris muscle
8- Extensor carpi ulnaris muscle
9- Extensor digiti minimi muscle
10- Supinator muscle
11- Abductor pollicis longus muscle
12- Extensor pollicis brevis muscle
13- Extensor pollicis longus muscle
14- Extensor indicis muscle
15- Basilic vein
16- Cephalic vein
17- Accessory cephalic vein
18- Dorsal venous network of the hand
19- Posterior interosseous artery

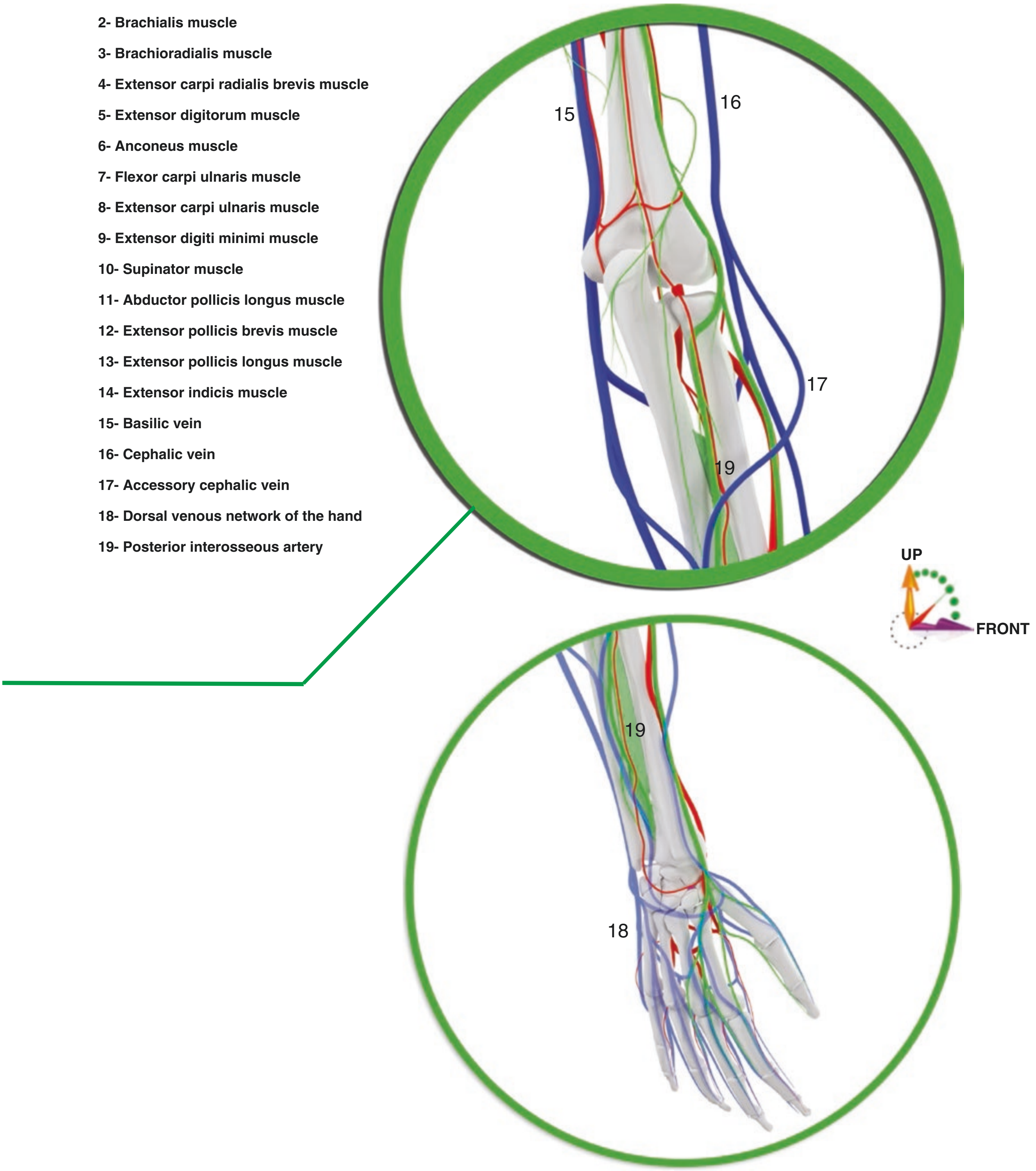


Figure R6. Vascular relations of the radial nerve in the forearm.

medially before moving away from it at the distal third of the forearm.

In the posterior face of the forearm, the deep branch of the radial nerve faces the posterior interosseous nerve of the forearm medially (Figure R6).

Collateral Branches

The radial nerve gives rise to cutaneous and muscular collateral branches (Figure R2):

- Muscular branches: superior and inferior nerves of the medial head of the triceps brachii, nerves of the anconæus muscle, long head of the triceps brachii, lateral head of the triceps brachii, brachioradialis and extensor radialis carpi longus (Figures R3 and R5)
- Cutaneous branches: posterior cutaneous nerve of the arm, heading towards the upper third of the posterior face of the arm; inferior lateral cutaneous nerve of the arm, heading towards the lower third of the posterior lateral face of the arm; and posterior cutaneous nerves of the forearm (Figures R3 and R5)

These cutaneous ramifications innervate the posterior face of the arm between the territory of the axillary nerve laterally and the medial cutaneous nerve of the arm and forearm medially.

Terminal Branches

A few centimetres above the elbow pit, the radial nerve divides itself into two branches: anterior and posterior (Figure R2).

The anterior branch is sensitive. It goes under the brachioradialis muscle in its sheath along the forearm. It faces the radial artery medially in the two superior thirds of the forearm. Behind, it successively faces the supinator muscle, pronator teres and flexor digitorum superficialis. At the lower third of the forearm, it separates from the radial artery and goes towards the forearm's posterior area (Figures R3 and R6).

It divides itself at the same level as or above the distal epiphysis of the radius into three branches: lateral, intermediate and medial. The lateral ramus is headed towards the lateral part of the thenar eminence and the intermediate ramus towards its medial part as well as the lateral part of the index finger at the level of its first phalange. The medial ramus is headed towards the second interosseous space, at the dorsal faces of the first phalanges of the index and middle fingers (Figures R5, R9 and R11).

The posterior branch, which is a motor branch, is also called posterior interosseous nerve. It goes through the fibrous arch of the superficial bundle of the supinator muscle, also known as arcade of Frohse, in order to join the posterior compartment of the forearm. It goes down behind and laterally, between the two heads of the supinator muscle, which is innervated by this posterior branch. This spot is an anatomical landmark, situated 2 cm under the elbow pit (Figure R3).

Near its origin, the nerve is crossed by the lateral branches of the radial recurrent artery and vein. The posterior interosseous nerve goes down before the radiohumeral joint, and under the superficial fibres of the supinator muscle, of which the proximal part of the aponeurosis represents the arcade of Frohse. After crossing it, the nerve goes in the posterior compartment of the forearm and then around the external border of the radius and goes out between the fibres of the supinator muscle before continuing towards the distal part of the forearm.

The posterior branch is then situated between the two posterior muscular planes of the forearm. It faces successively the abductor pollicis longus and extensor pollicis brevis in front and then faces the interosseous membrane. In behind, it faces the extensor pollicis longus and the extensor indicis (Figure R5).

The terminal posterior branch of the radial nerve gives rise to muscular branches heading towards the posterior compartment of the forearm. After going 4 cm under and along the supinator muscle, the nerve gives off seven branches for the extensor carpi ulnaris, extensor digitorum brevis, extensor digitorum, extensor pollicis longus and brevis,, extensor digiti minimi and extensor indicis. It sometimes gives off branches for both extensor radialis carpi muscles (Figures R5, R9 and R14).

Motor Function

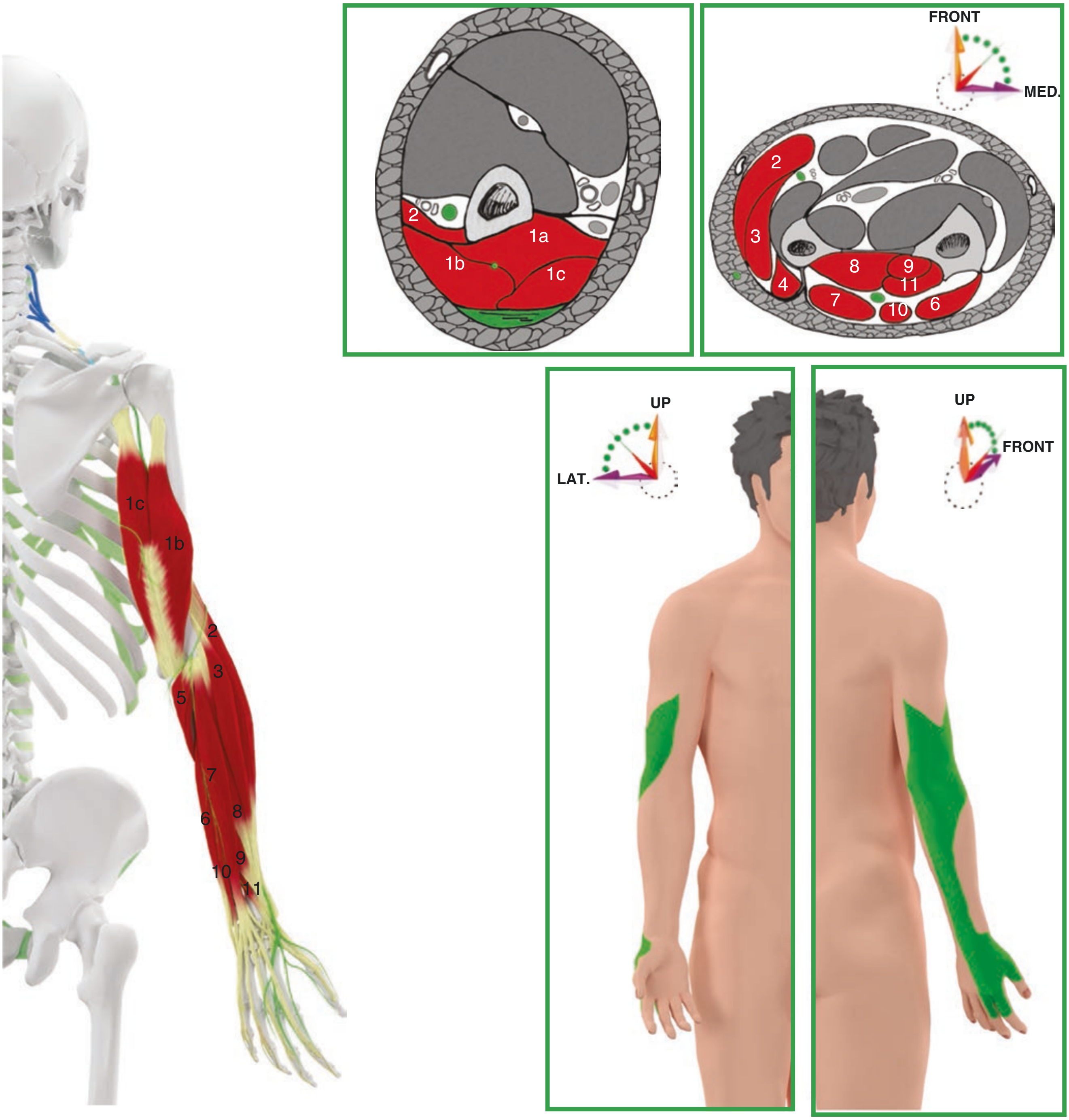
The posterior branch innervates all of the extensor muscles in the wrist and fingers except the extensor radialis carpi longus, which is innervated by the radial nerve trunk itself.

1- Triceps brachii muscle
  1a- Medial head
  1b- Lateral head
  1c- Long head

2- Brachioradialis muscle
3- Extensor carpi radialis longus muscle
4- Extensor carpi radialis brevis muscle
5- Anconeus muscle

6- Extensor carpi ulnaris muscle
7- Extensor digitorum muscle
8- Abductor pollicis longus muscle
9- Extensor pollicis brevis muscle

10- Extensor digiti minimi muscle
11- Extensor pollicis longus muscle


2
1a
1b
1c
FRONT
MED.
2
3
4
8
9
11
7
10
6
UP
LAT.
UP
FRONT
1c
1b
2
3
5
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9
10
11

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Figure R7. Motor and sensitive innervation of the radial nerve.

The Radial Nerve

1- Pectoralis major muscle
2- Pectoralis minor muscle
3- Cephalic vein
4- Deltoid muscle
5- Short head of the biceps brachii muscle
6- Coracobrachialis muscle
7- Tendon of the long head of the biceps brachii muscle
8- Latissimus dorsi muscle
9- Humerus
10- Teres major muscle
11- Lateral head of the triceps brachii muscle
12- Circumflex artery and nerve
13- Long head of the triceps brachii muscle
14- Teres minor muscle
15- Infraspinatus muscle
16- Scapula
17- Medial cutaneous nerve of arm
18- Median nerve
19- Medial cutaneous nerve of forearm
20- Ulnar nerve
21- Radial nerve
22- Musculocutaneous nerve
23- Subscapularis muscle
24- Brachial vein
25- Brachial artery
26- Serratus anterior muscle
27- Biceps brachii muscle
28- Brachialis muscle
29- Brachioradialis muscle

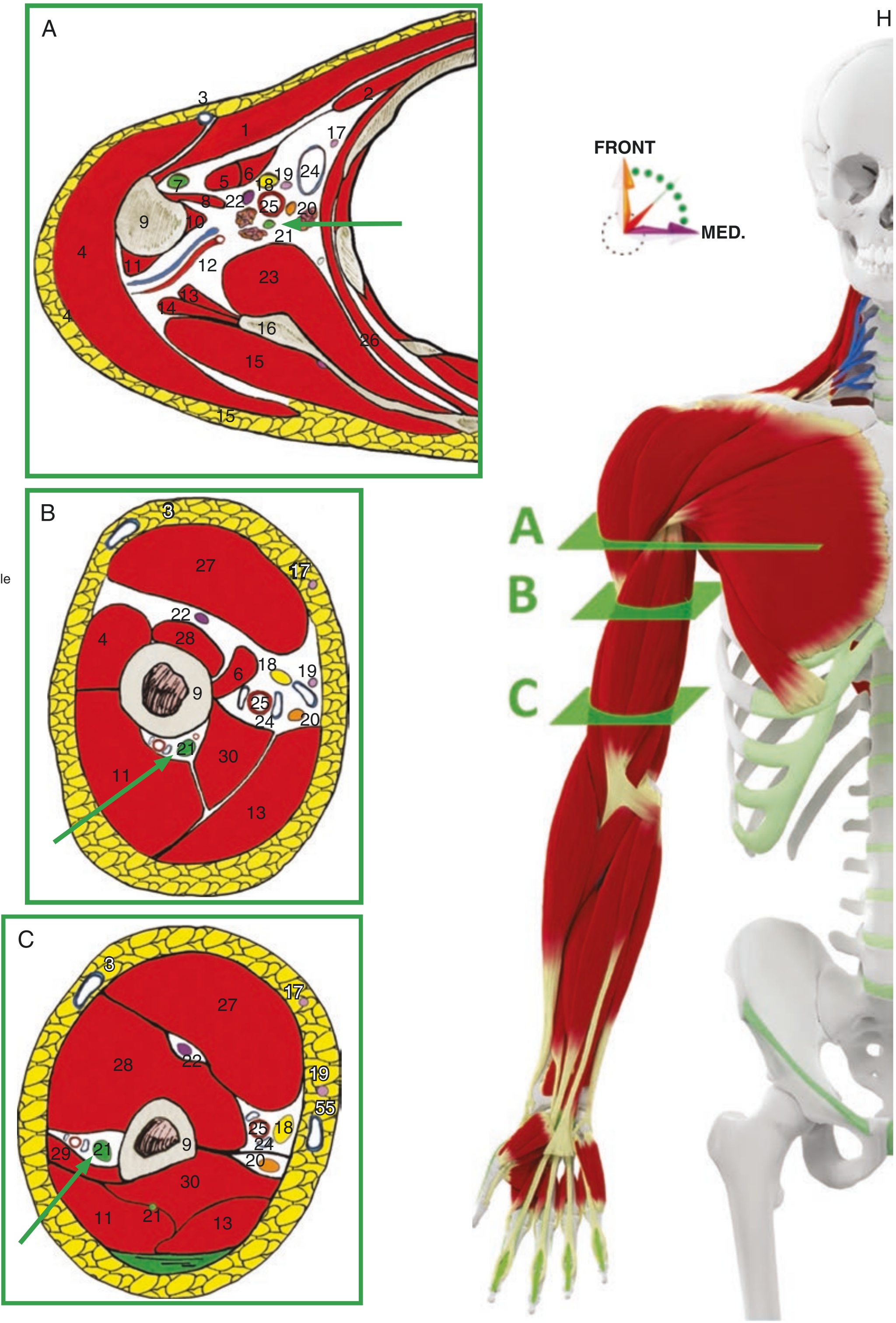
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Figure R8. Relations of the radial nerve in the arm, axial sections.

30- Medial head of the triceps brachii muscle
31- Extensor carpi radialis longus muscle
32- Extensor carpi radialis brevis muscle
33- Tendon of epicondyle muscles
34- Anconeus muscle
35- Olecranon
36- Tendon of the triceps brachii muscle
37- Tendon of the median epycondylian muscles
38- Pronator teres muscle
39- Ulna
40- Radius
41- Palmaris longus muscle
42- Flexor carpi radialis muscle
43- Flexor digitorum superficialis muscle
44- Flexor digitorum profundus muscle
45- Flexor pollicis longus muscle
46- Flexor carpi ulnaris muscle
47- Abductor pollicis longus muscle
48- Extensor pollicis brevis muscle
49- Extensor pollicis longus muscle
50- Extensor digitorum muscle
51- Extensor digiti minimi muscle
52- Extensor carpi ulnaris muscle
53- Extensor indicis muscle
54- Median vein of the forearm
55- Basilic vein
56- Radial artery and vein
57- Ulnar artery and vein
58- Pronator quadratus muscle

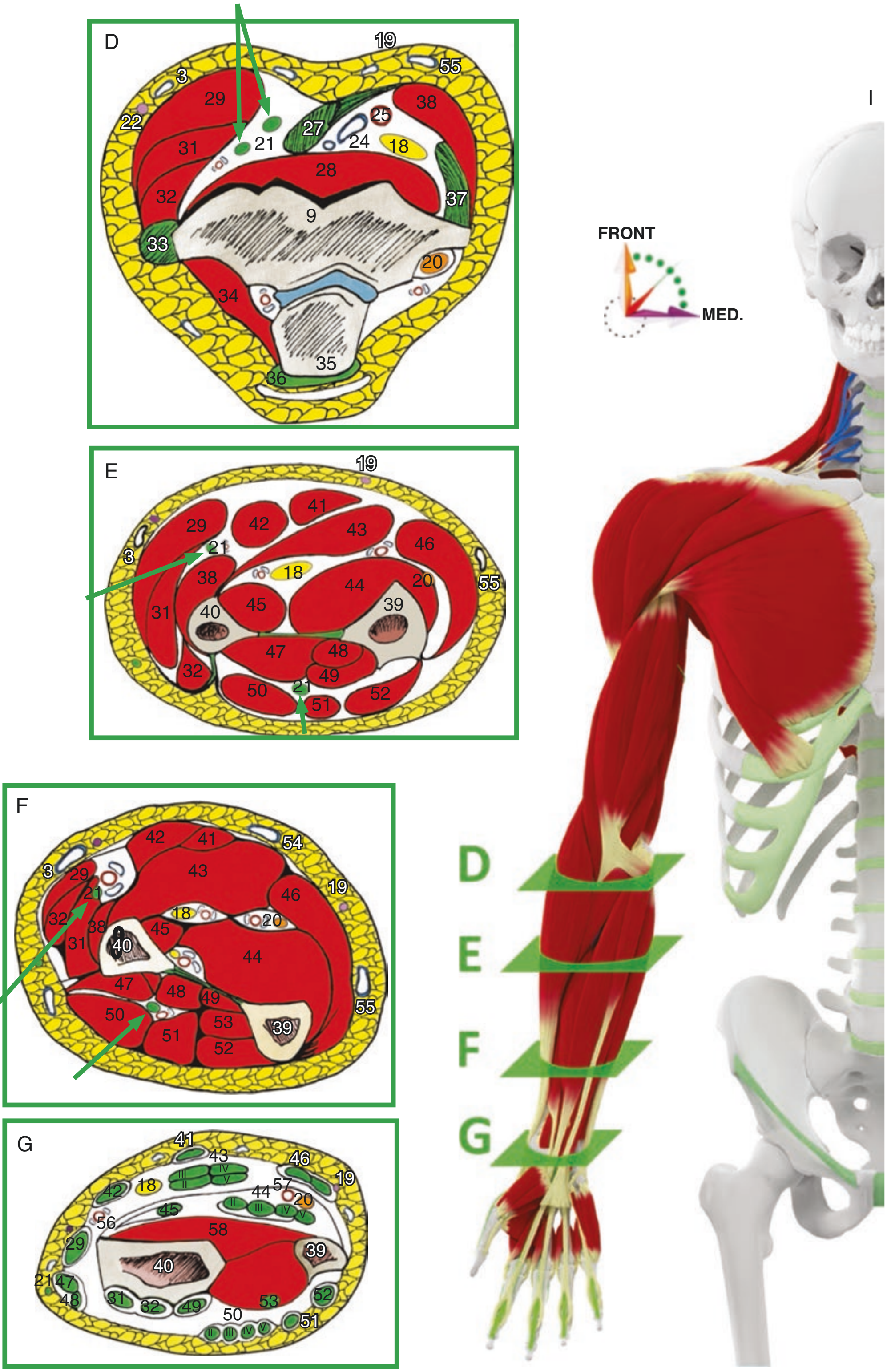
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Figure R9. Relations of the radial nerve in the elbow and forearm, axial sections.

The deficit caused by a compression of the posterior branch of the nerve leaves the wrist in a persisting extension, making it appear laterally inclined.

In the end, the radial nerve is responsible for the extension of the forearm on the arm, of the wrist on the forearm and of the fingers (Figure R7).

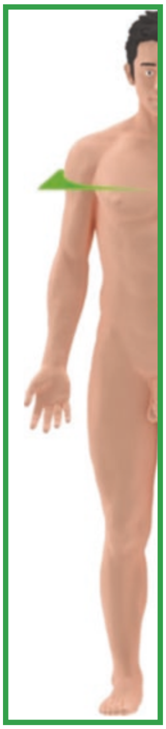
Sensitive Function

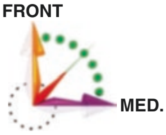
The sensitive function is situated at the level of the superficial branch. It innervates the dorsal face of the first commissure at the level of the hand, the dorsal face of the thumb and the dorsal faces of the index and middle fingers until the junction between the second and third phalanges (Figure R7).

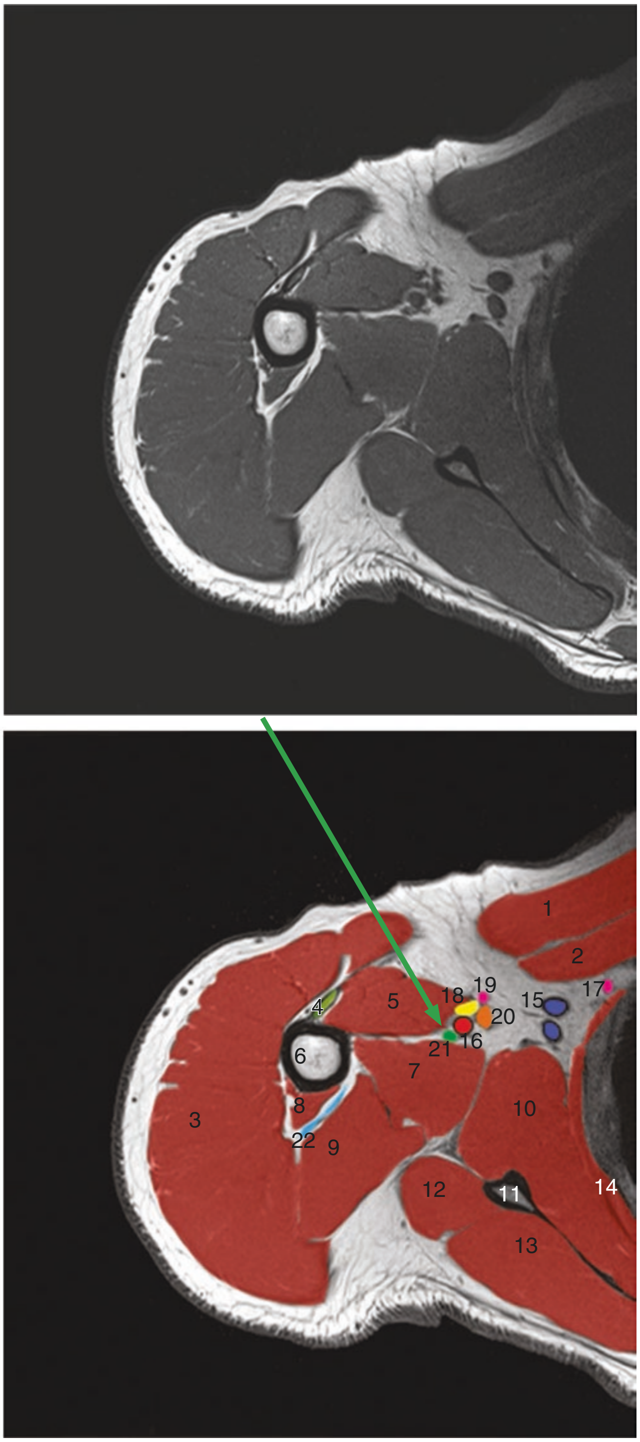
Anastomoses

With:

- The musculocutaneous nerve
- The median nerve at the level of the thumb
- The ulnar nerve in the dorsal face of the hand
- The medial cutaneous nerves of the forearm and arm







1- Pectoralis major muscle

2- Pectoralis minor muscle

3- Deltoid muscle

4- Long head of the biceps brachii muscle

5- Latissimus dorsi muscle

6- Humerus

7- Teres major muscle

8- Lateral head of the triceps brachii muscle

9- Medial head of the triceps brachii muscle

10- Subscapularis muscle

11- Scapula

12- Teres minor muscle

13- Infraspinatus muscle

14- Serratus anterior

15- Brachial vein

16- Brachial artery

17- Medial cutaneous nerve of arm

18- Median nerve

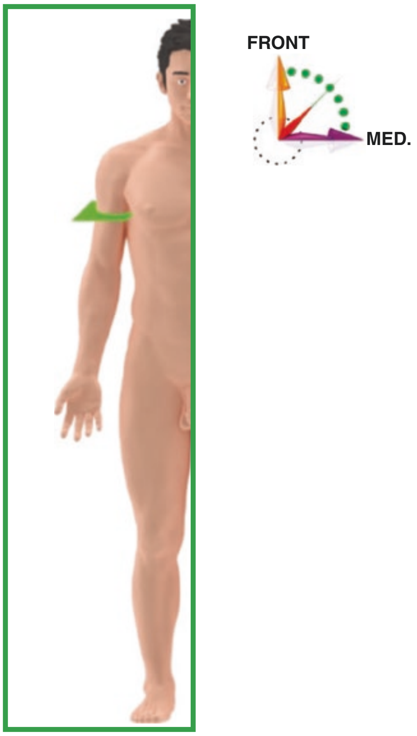
19- Medial cutaneous nerve of forearm

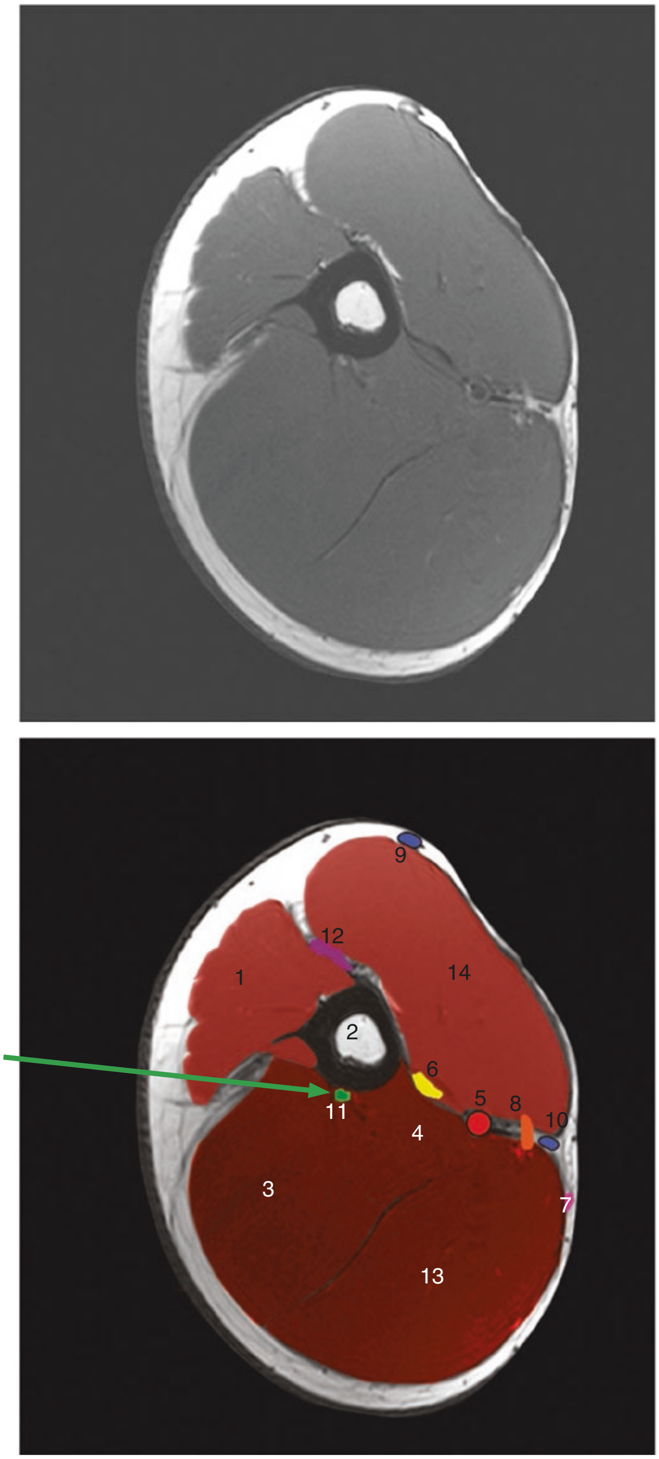
20- Ulnar nerve

21- Radial nerve

22- Axillary nerve

Figure R10. MRI scans in the shoulder through the radial nerve.





1- Deltoid muscle

2- Humerus

3- Lateral head of the triceps brachii muscle

4- Medial head of the triceps brachii muscle

5- Brachial artery

6- Median nerve

7- Medial cutaneous nerve of forearm

8- Ulnar nerve

9- Cephalic vein

10- Basilic vein

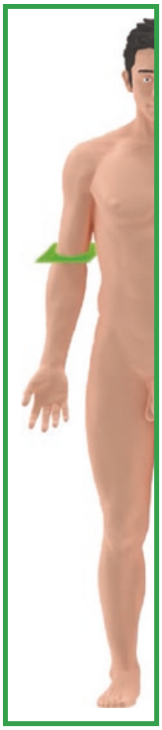
11- Radial nerve

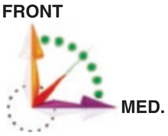
12- Musculocutaneous nerve

13- Long head of the triceps brachii muscle

14- Biceps brachii muscle

Figure R11. MRI scans at the proximal third of the arm through the radial nerve.





1- Biceps brachii muscle

2- Brachioradialis muscle

3- Brachialis muscle

4- Lateral head of the triceps brachii muscle

5- Humerus

6- Long head of the triceps brachii muscle

7- Medial head of the triceps brachii muscle

8- Cephalic vein

9- Radial nerve

10- Musculocutaneous nerve

11- Brachial artery

12- Brachial vein

13- Median nerve

14- Basilic vein

15- Ulnar nerve

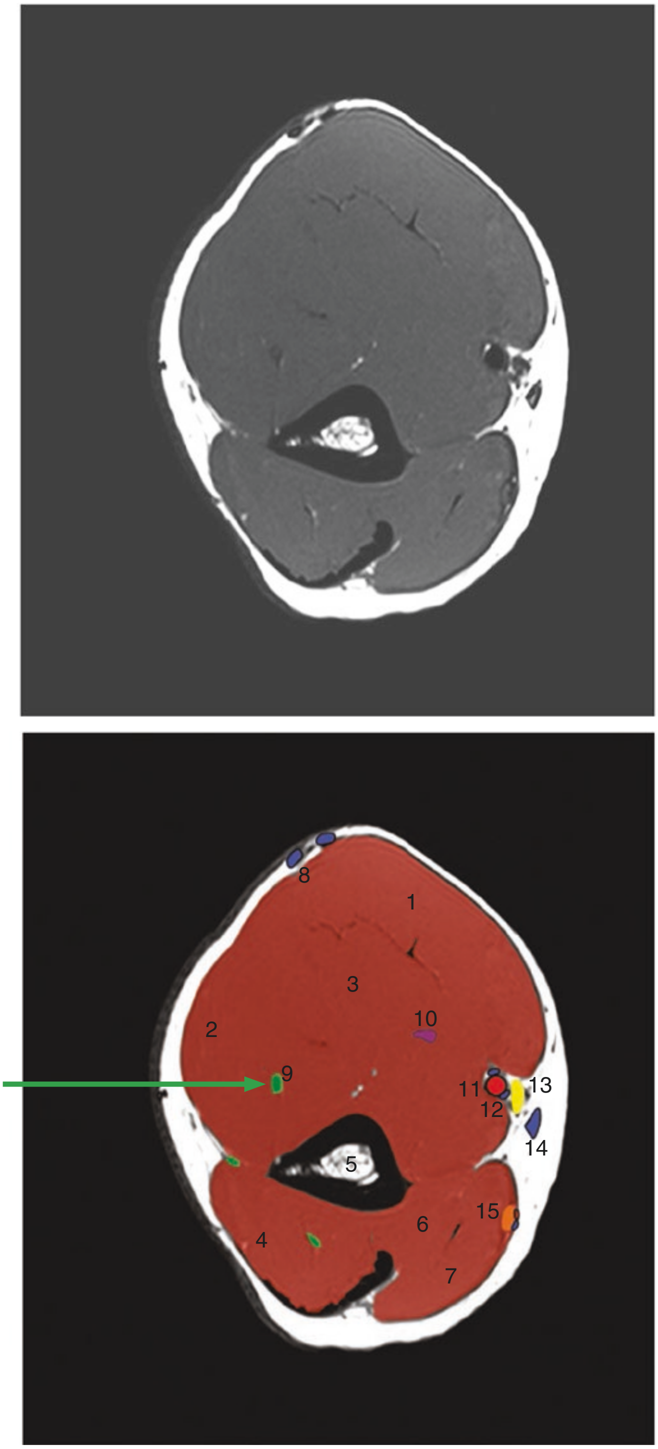
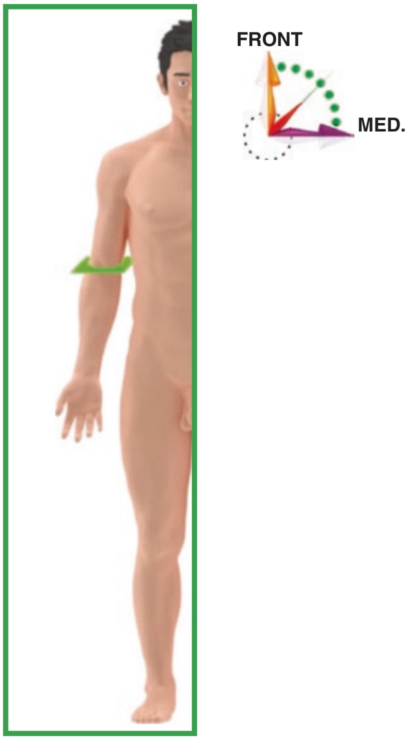
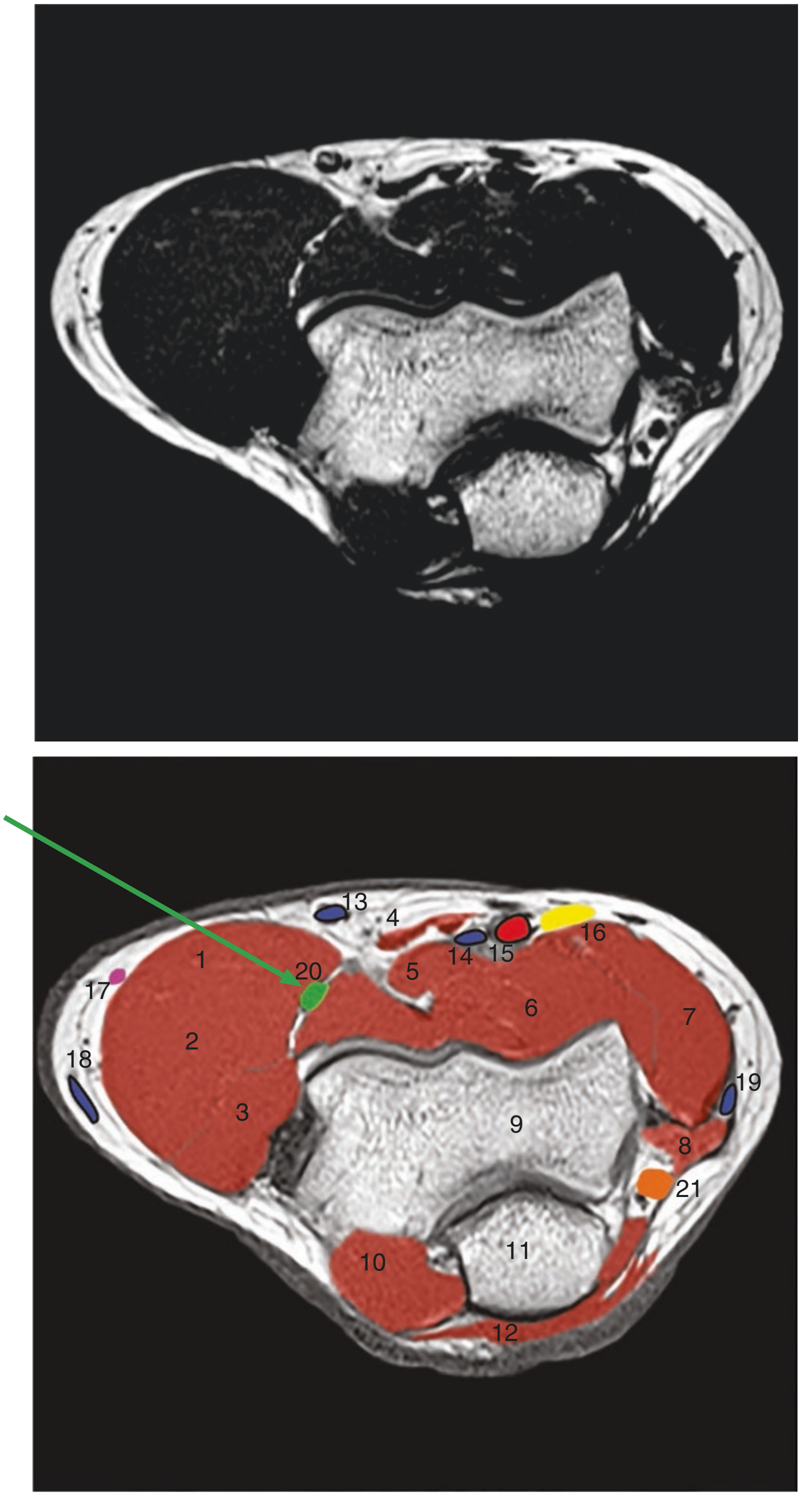


Figure R12. MRI scans at the distal third of the arm through the radial nerve.





1- Brachioradialis muscle

2- Extensor carpi radialis longus muscle

3- Extensor carpi radialis brevis muscle

4- Biceps brachii muscle

5- Tendon of the long head of biceps

6- Brachialis muscle

7- Pronator teres muscle

8- Tendon of the median epycondylian muscles

9- Humerus

10- Anconeus muscle

11- Ulna

12- Triceps brachii muscle

13- Medial vein at the elbow

14- Brachial vein

15- Brachial artery

16- Median nerve

17- Musculocutaneous nerve

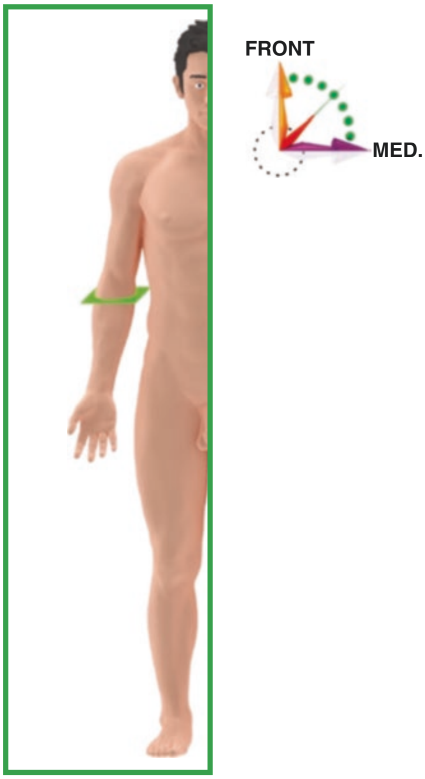
18- Cephalic vein

19- Basilic vein

20- Radial nerve

21- Ulnar nerve

Figure R13. MRI scans in the elbow through the radial nerve.



1- Flexor carpi radialis muscle

2- Flexor digitorum superficialis muscle

3- Flexor carpi ulnaris muscle

4- Flexor pollicis longus muscle

5- Extensor carpi radialis brevis muscle

6- Flexor digitorum profundus muscle

7- Radius

8- Ulna

9- Interosseous membrane of the forearm

10- Posterior compartment of the extensor digitorum muscles

11- Extensor carpi muscle

12- Radial artery and vein

13- Radial nerve

14- Median nerve

15- Ulnar nerve

16- Ulnar artery and vein

17- Basilic vein

18- Anterior interosseous artery, vein and nerve

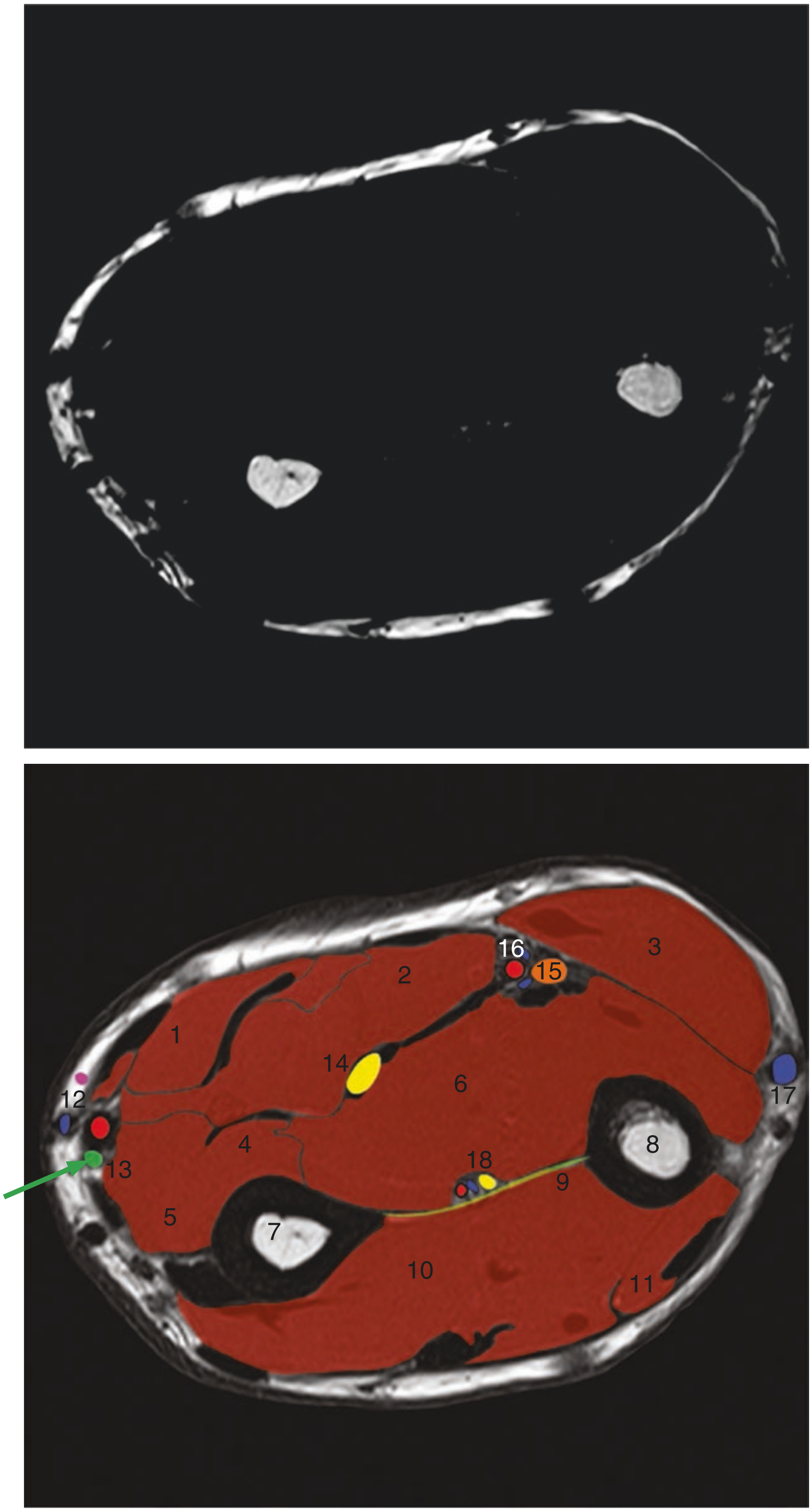


Figure R14. MRI scans in the forearm through the radial nerve.

Pathology

Pathology concerns:

- Direct injuries of the nerve trunk, at the level of its osteofibrous tunnel in the arm, when a mid-shaft humeral fracture occurs (see above)
- The posterior interosseous nerve syndrome (see below)

Posterior Interosseous Nerve Syndrome

The posterior interosseous nerve, which is the posterior terminal branch of the radial nerve, takes its origin a few centimetres below the elbow pit. Just after its origin, it penetrates between the two planes of fibres of the supinator muscle. At this level, the proximal border of the superficial fibres constitutes the arcade of Frohse. As a reminder, this branch has a motor function for the extensor muscles in the wrist aside from the extensor carpi radialis longus (Figure R15).

Aetiology

- Compression: This is an entrapment neuropathy that happens in most cases when the muscles that surround the origin of the posterior interosseous nerve are overused. These circumstances can be found in repetitive movements of pronation and supination. The compression's most common point is situated at the level of the arcade of Frohse, at the entry point of the nerve in the supinator muscle. This entrapment neuropathy is particularly frequent amongst tennis players.
- Traction: The gestures implicated in this syndrome are also factors of traction on the nerve at this level.

Clinical Signs

Sensitive signs: Pain sensation can happen without warning signs. It is dull and generally located at the proximal and lateral part of the forearm. It can appear after a variable amount of time when performing repeated gestures of the distal extremity whilst pronating the forearm, such as repeated mouse clicks whilst working on a computer.

Motor signs: The patient can show a loss of extension of the fingers, especially in the metacarpus and phalanges. Wrist extension is preserved by the action of the extensor radialis carpi longus. However, since the extensor carpi ulnaris is innervated by the posterior interosseous nerve, extension of the wrist is accompanied by a lateral deviation.

Clinical Forms

When this syndrome evolves over a large duration of time, an amyotrophy of the posterior compartment of the forearm can develop. It does not impact the brachioradialis or the extensor radialis carpi longus muscles.

An incomplete motor injury can affect only the extension of the fourth and fifth fingers, appearing like an ulnar injury.

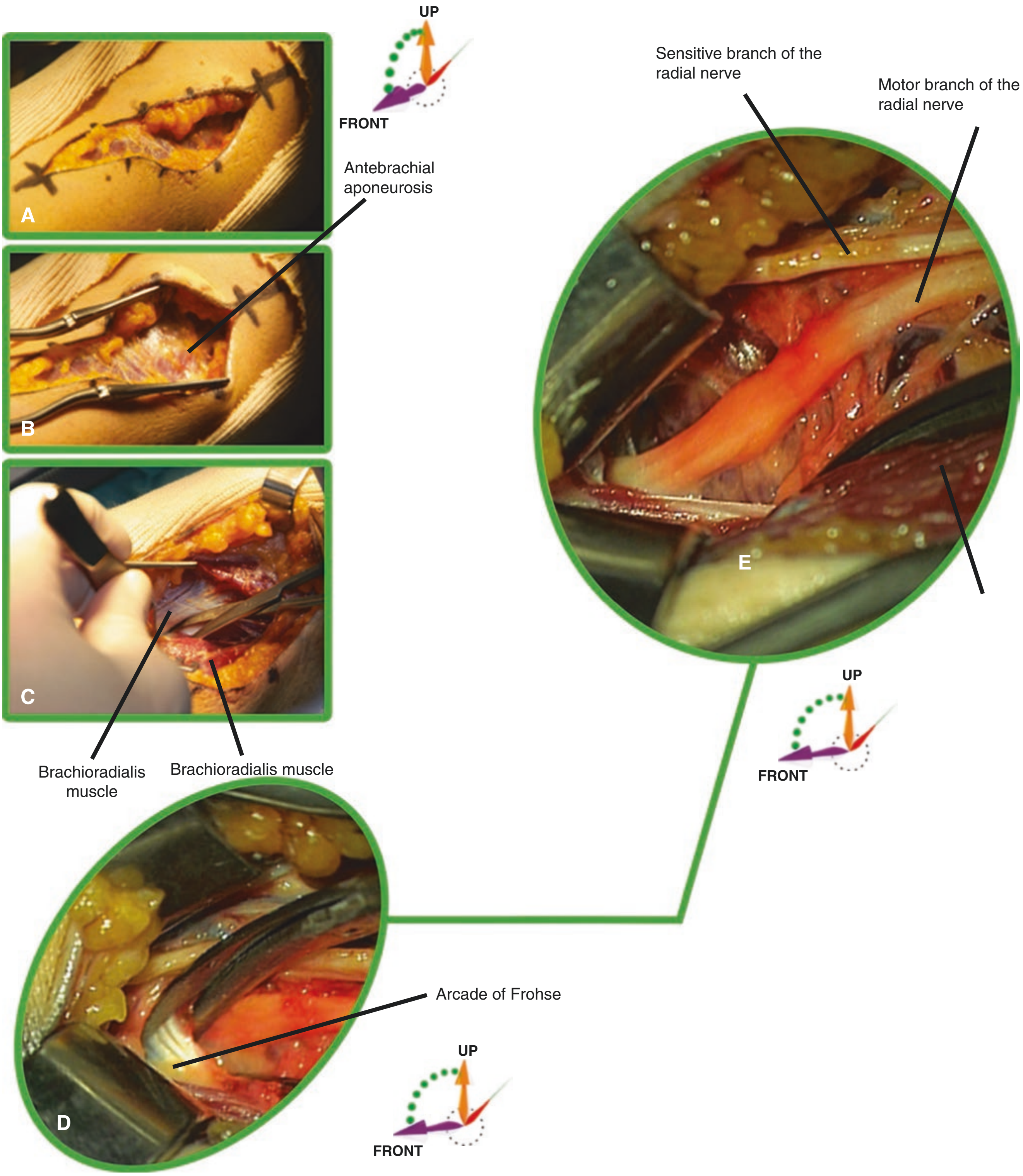
Explorations

Elbow radiographies must be systematically executed:

- An electrophysiological study confirms the injured area.
- An MRI scan also allows for the elimination of differential diagnoses.

Treatment

It is surgical and indicated after 3 months of conservative treatment with no improvement or a worsening of symptomatology. If the cause is an expansive process, then resection is indicated in the first instance in order to limit the potentially irreversible injury of the posterior interosseous nerve. Postsurgical results are positive in a majority of publications.


UP
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Sensitive branch of the radial nerve
Motor branch of the radial nerve
Antebrachial aponeurosis
A
B
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UP
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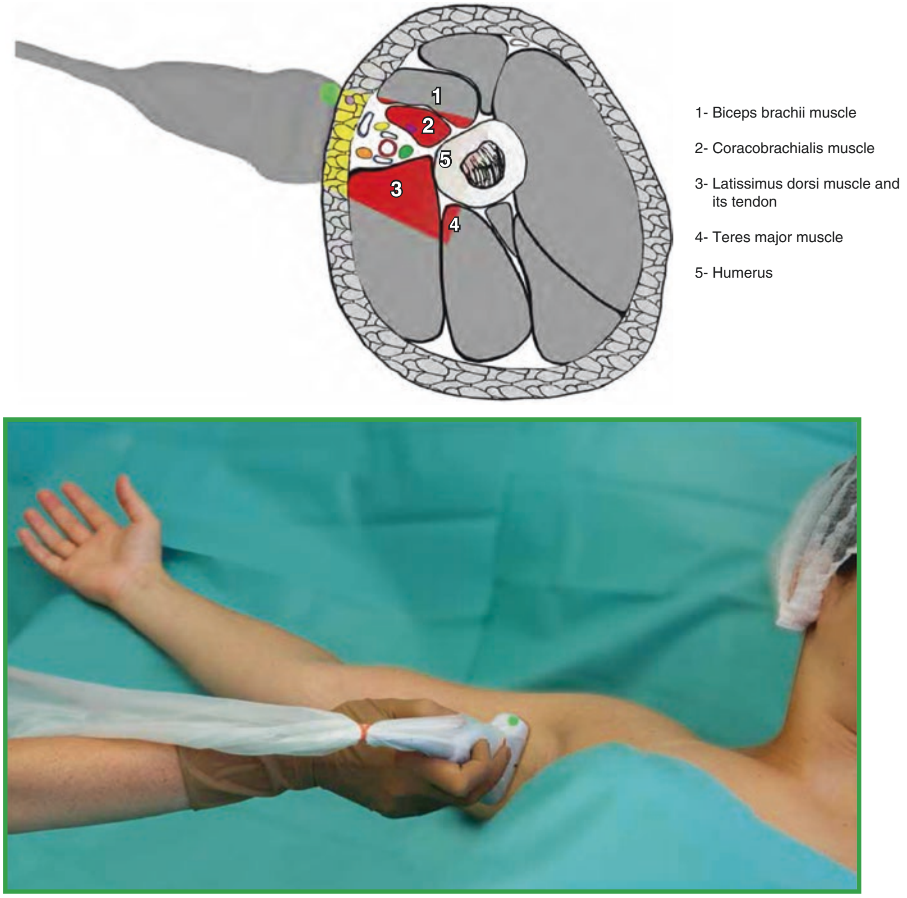
Brachioradialis muscle
Brachioradialis muscle
Arcade of Frohse
D
UP
FRONT

Figure R15. Pathology of the radial nerve. Decompression surgery of the posterior interosseous branch at the level of the arcade of Frohse: (**a**) cutaneous incision; (**b**) insertion of the retractor; (**c**) approach to the radial nerve; (**d**) section of the arcade of Frohse; (**e**) decompression of the nerve's motor branch.

Morphological Data: Sono Anatomy

At the axillary cavity, the radial nerve is in a dorsolateral position with respect to the artery. It is in contact with the tendon of the latissimus dorsi muscle, at times difficult to identify, hiding behind the ultrasonic strengthening of the vascular flow. During sono-anatomical monitoring of the radial nerve, when the lower edge of the tendon of the latissimus dorsi is reached, the radial nerve can be identified, leaking deeply (dorsally) to the top of the humeral groove of the radial nerve.

It is important to apply the "elevator" technique to follow the path of the radial nerve, after first identifying the specific neurological target (the radial nerve itself, or one of its collateral or terminal branches). This nerve tracking technique requires a good understanding of the nerve's path beforehand.


1
2
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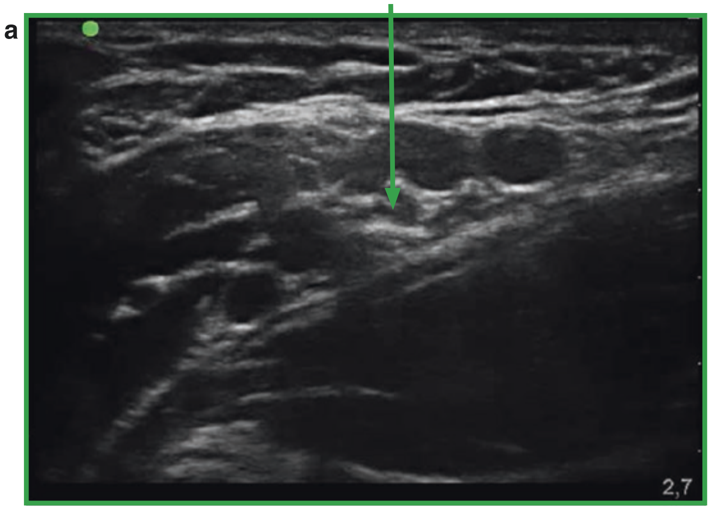
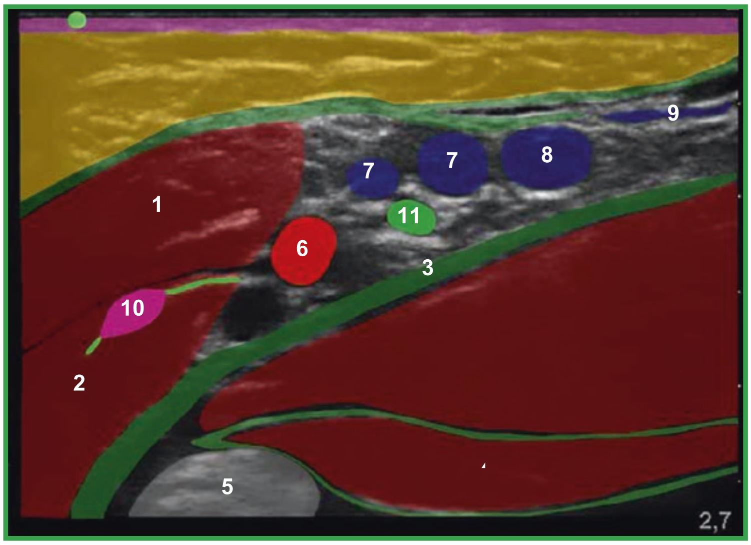
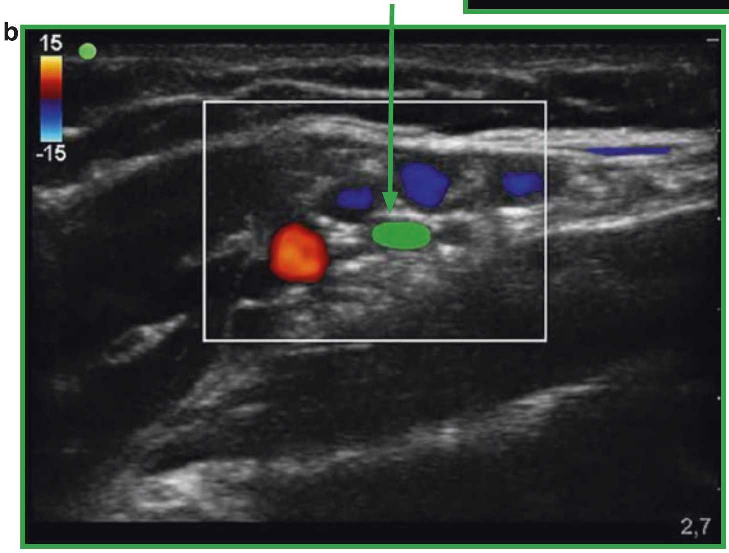
1- Biceps brachii muscle
2- Coracobrachialis muscle
3- Latissimus dorsi muscle and its tendon
4- Teres major muscle
5- Humerus

Figure R16. Ultrasound probe optimal positioning to visualize the radial nerve.





1- Biceps brachii muscle
2- Coracobrachialis muscle
3- Latissimus dorsi muscle and its tendon
4- Teres major muscle
5- Humerus
6- Brachialis artery
7- Brachialis veins
8- Cephalic vein
9- Basilic vein
10- Musculocutaneous nerve
11- Radial nerve



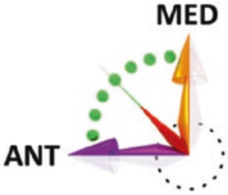


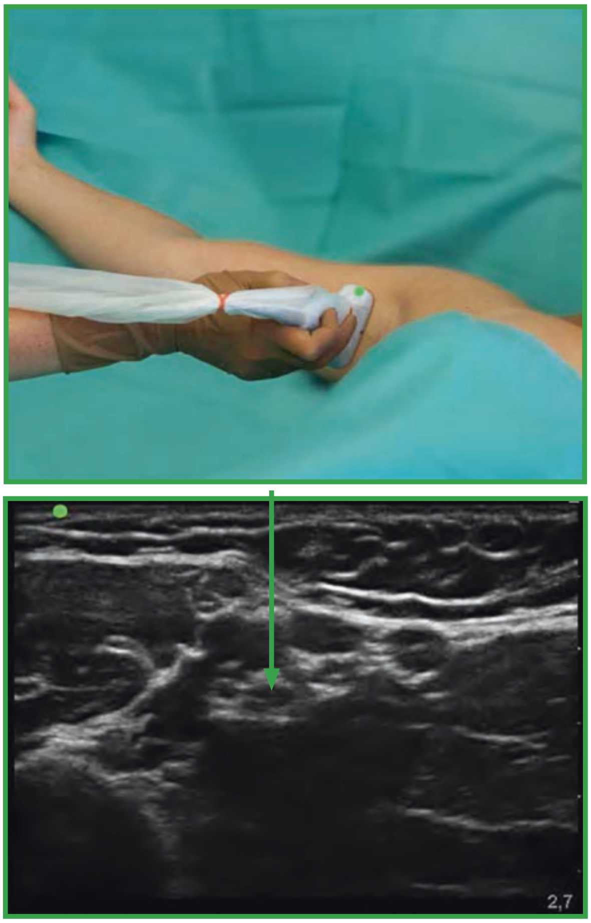
Figure R17. (**a**) Ultrasound transversal view of the radial nerve at distal tier of the axillary pit. (**b**) Doppler mode view.

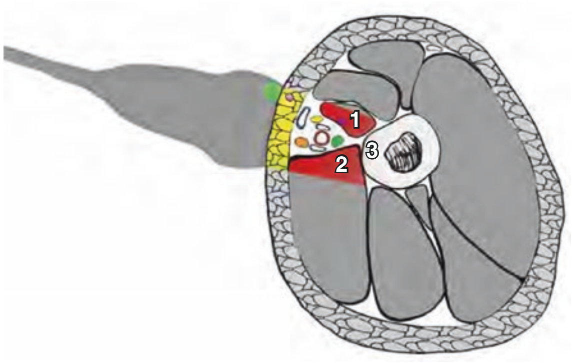
Morphological Data: Sonoanatomy

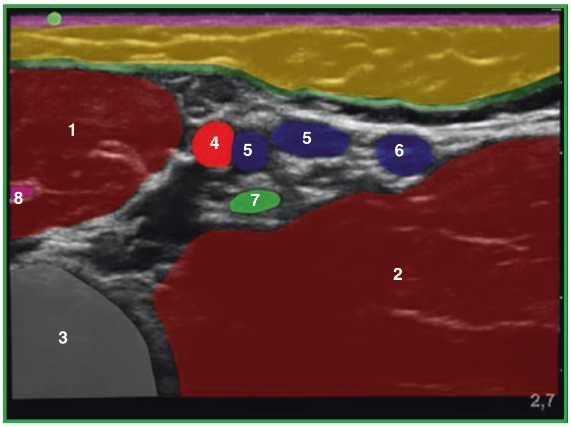
The radial nerve leaves the axillary fossa, resting on the teres major muscle, and moves caudally, dorsally towards the lateralized and then bypasses the humerus in the spiral groove at the insertion of the deltoid, emitting the first collateral (posterior cutaneous nerve of the forearm).

It passes through the lateral intermuscular septum to the anterior chamber of the arm and travels in the lateral bicipital groove between the brachialis and brachioradialis muscles. The radial nerve is subdivided at this level into two terminal branches:

- The superficial branch, exclusively sensitive, descends vertically against the deep face of the brachioradialis muscle accompanied by the radial artery and superficially crosses the tendon of the brachioradialis muscle.
- The deep, essentially motor branch descends between the two leaders of the supinator muscle.







1- Coracobrachialis muscle
2- Latissimus dorsi muscle
3- Humerus
4- Brachialis artery
5- Brachialis veins
6- Cephalic vein
7- Radial nerve
8- Musculocutaneous nerv

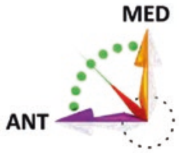
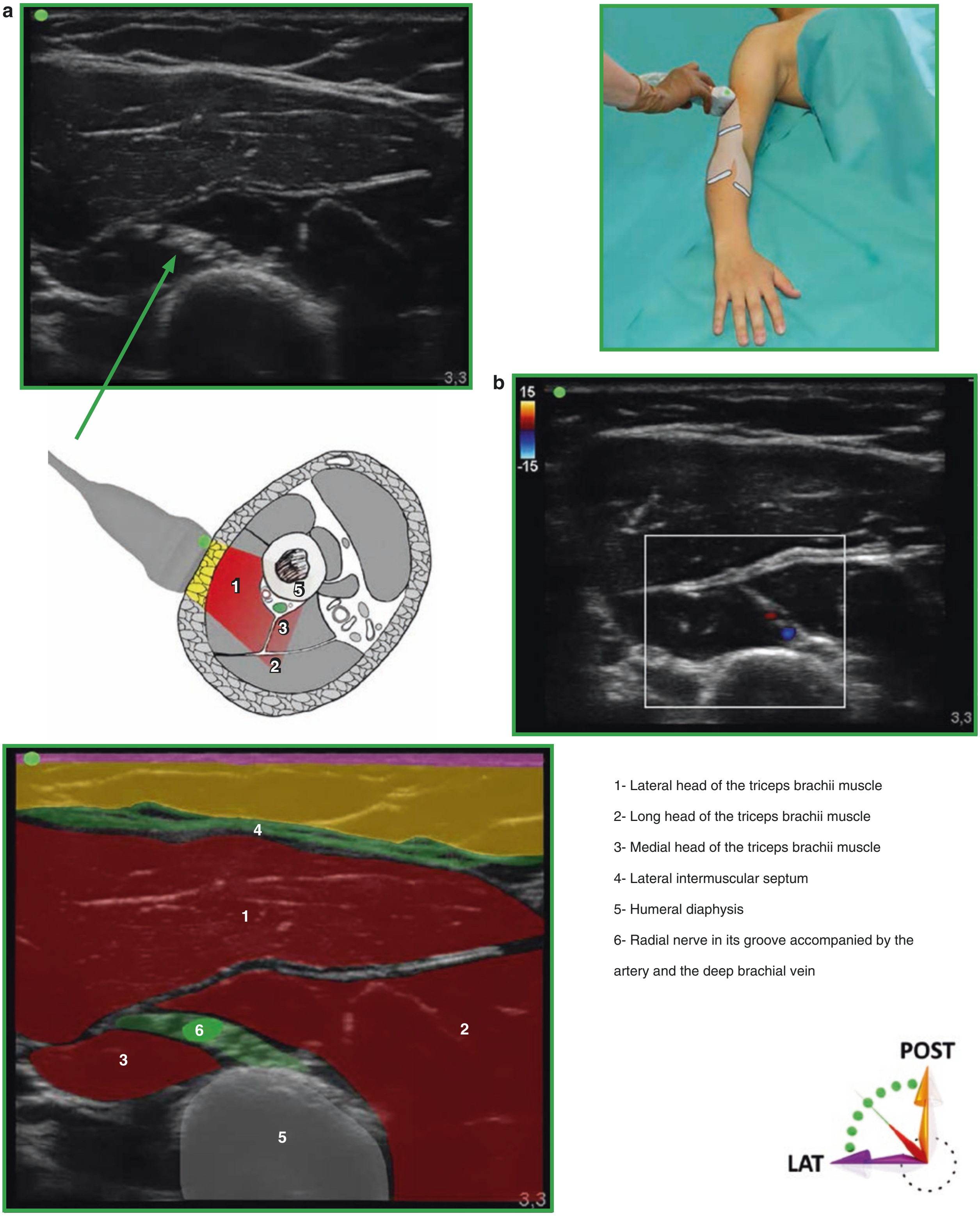


Figure R18. Ultrasound transversal views of the radial nerve at the inferior part of the tendon's latissimus dorsi muscle. At this level, the radial nerve runs towards the humeral groove, at the posterior surface of the humerus.



1- Lateral head of the triceps brachii muscle

2- Long head of the triceps brachii muscle

3- Medial head of the triceps brachii muscle

4- Lateral intermuscular septum

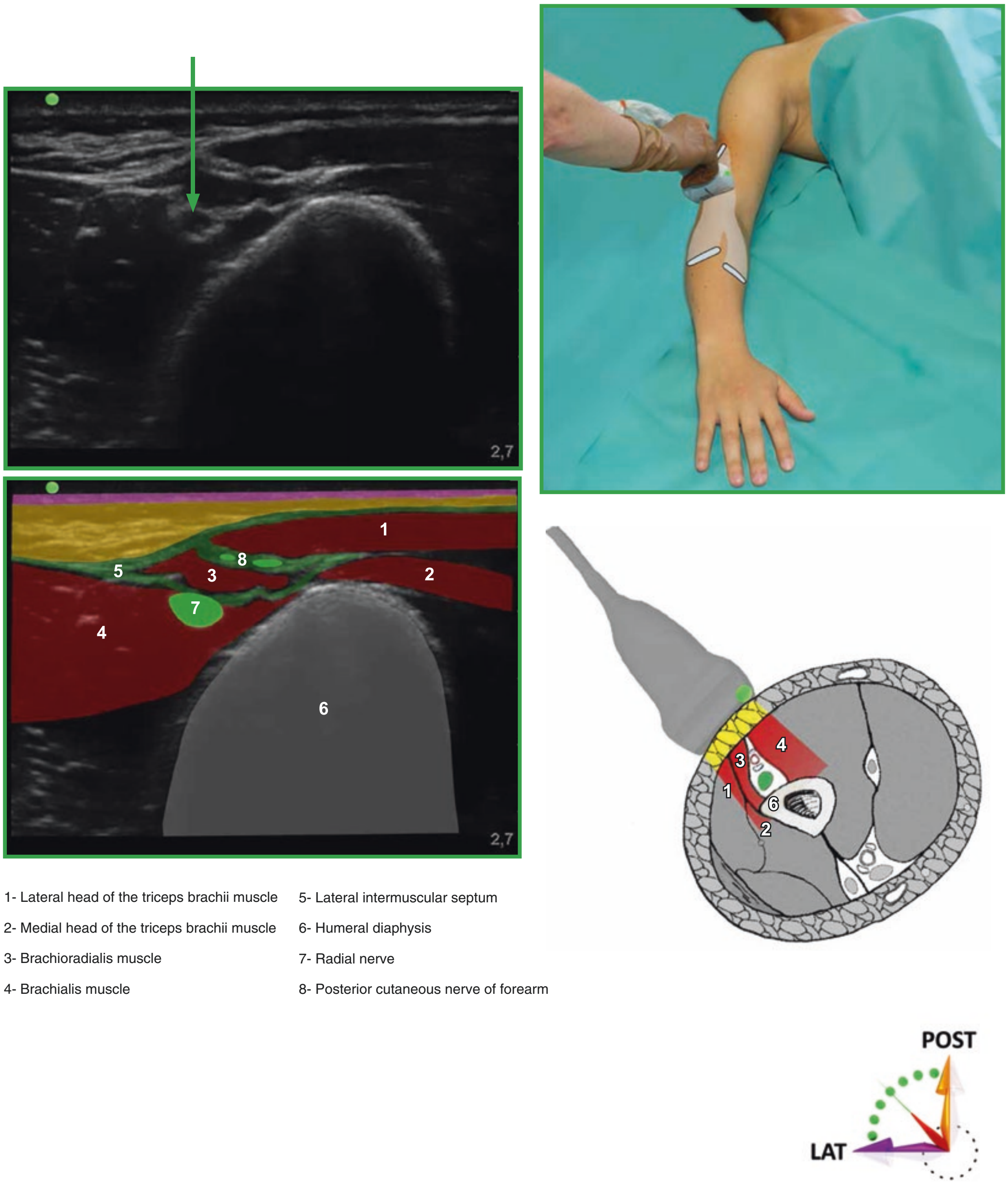
5- Humeral diaphysis

6- Radial nerve in its groove accompanied by the artery and the deep brachial vein

Figure R19. Ultrasound transversal view of the radial nerve at the entry of humeral groove. (**a**) Posterior view. (**b**) Doppler mode view.

Morphological Data: Sonoanatomy

In the brachial canal, unlike the median and ulnar nerves in which the position of the probe is identical, the radial nerve is much more dorsal, the patient's arm is oriented in internal rotation with one hand placed on the abdomen or in pronation. The probe is positioned perpendicular to the arm at the dorsal surface, the main reference being the radial nerve groove between the humerus and triceps brachii muscle. In this groove, the nerve is accompanied by the deep brachial artery.

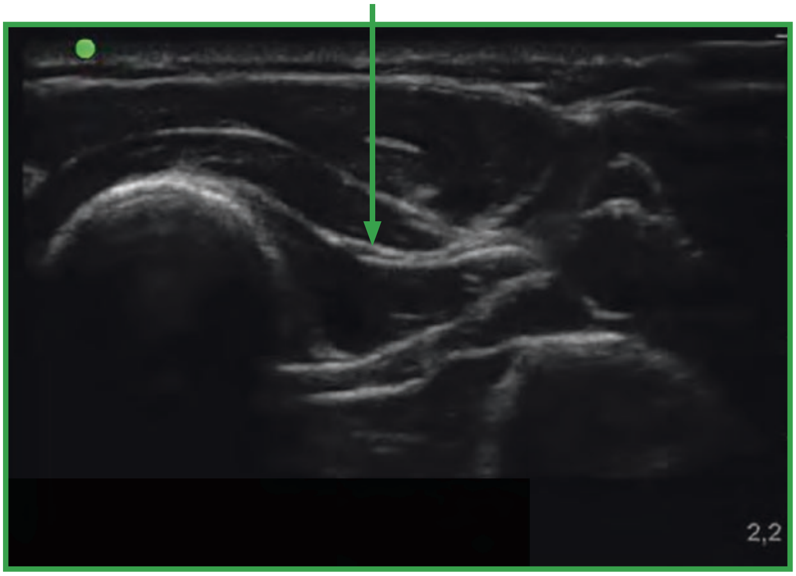


1- Lateral head of the triceps brachii muscle
2- Medial head of the triceps brachii muscle
3- Brachioradialis muscle
4- Brachialis muscle
5- Lateral intermuscular septum
6- Humeral diaphysis
7- Radial nerve
8- Posterior cutaneous nerve of forearm

Figure R20. Ultrasound transversal views of the radial nerve at the humeral groove exit.

The hand is in pronation, the forearm at 90° in flexion. The probe is proximally and transversely perpendicular to the forearm. The markers are muscular with the extensor digitorum and supinator muscles, and bony with the radius, ulna and head of the radius.

The nerve is located in the space between the two bundles of supinator muscle. It is also possible to carry out dynamic ultrasound by asking the patient to perform a pronation-supination movement.



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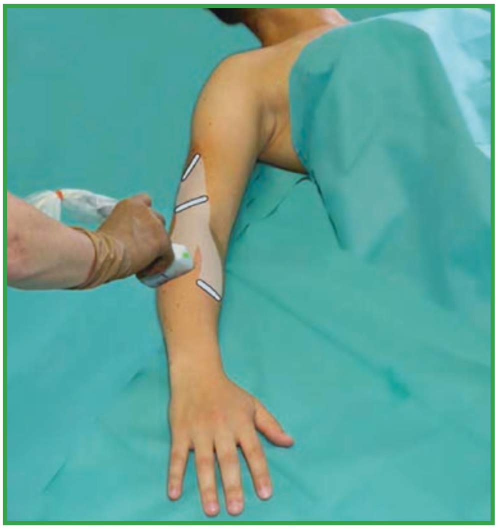

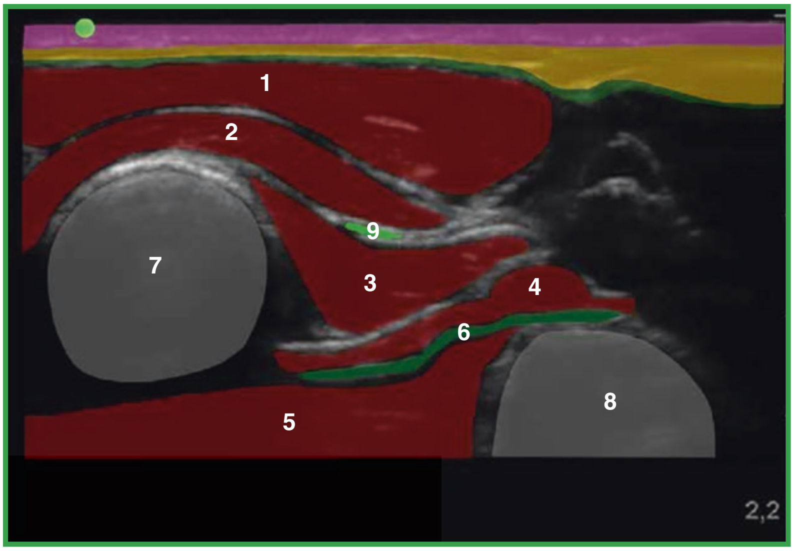

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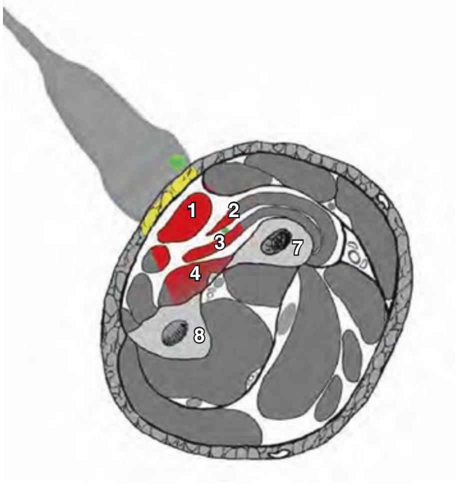


1- Extensor digitorum muscle
2- Superficial head of the supinator muscle
3- Deep head of the supinator muscle
4- Abductor pollicis longus muscle
5- Flexor digitorum profundus muscle
6- Interosseous membrane
7- Radius
8- Ulna
9- Radial nerve

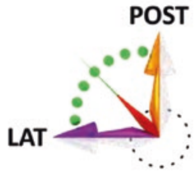
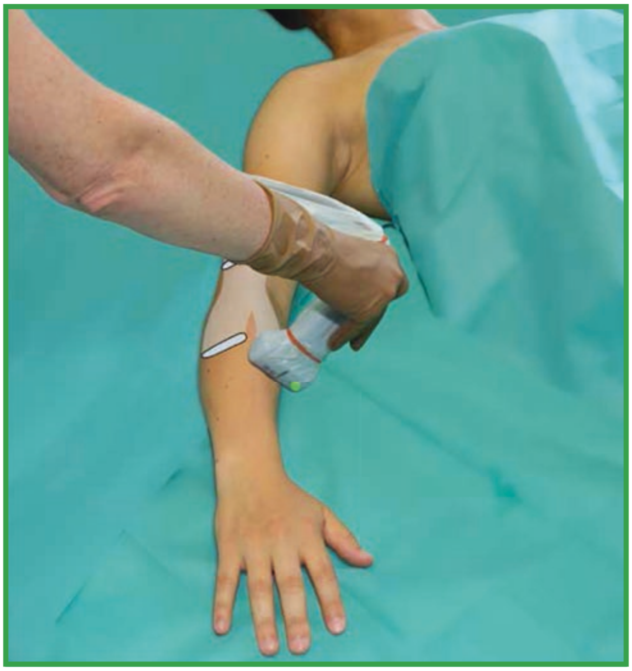


Figure R21. Ultrasound transversal views of the radial nerve motor branch at the level of Frohse’s arcade (proximal third).

To isolate the sensitive branch, the position is the same; it is achieved by repositioning the probe forwards, always in a transverse position, perpendicular to 90°. The hand is in pronation and the probe is in a more radial position.

The landmarks are muscular with the brachioradialis muscle above, vascular with the radial artery that adjoins the radial nerve at the upper two-thirds of the forearm.



1- Brachioradialis muscle
2- Superficial head of the supinator muscle
3- Deep head of the supinator muscle
4- Flexor pollicis longus muscle
5- Flexor carpi radialis muscle
6- Interosseous membrane
7- Radius
8- Radial artery
9- Anterior sensitive branche of the radial nerve
10- Motor branche of the radial nerve

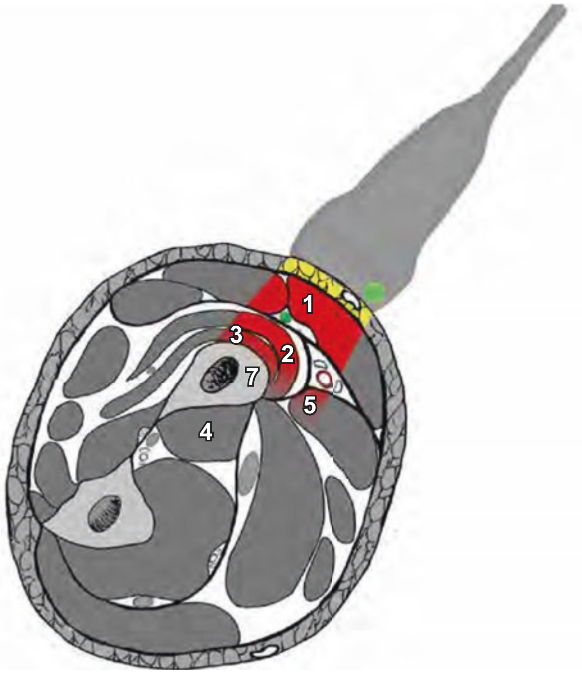
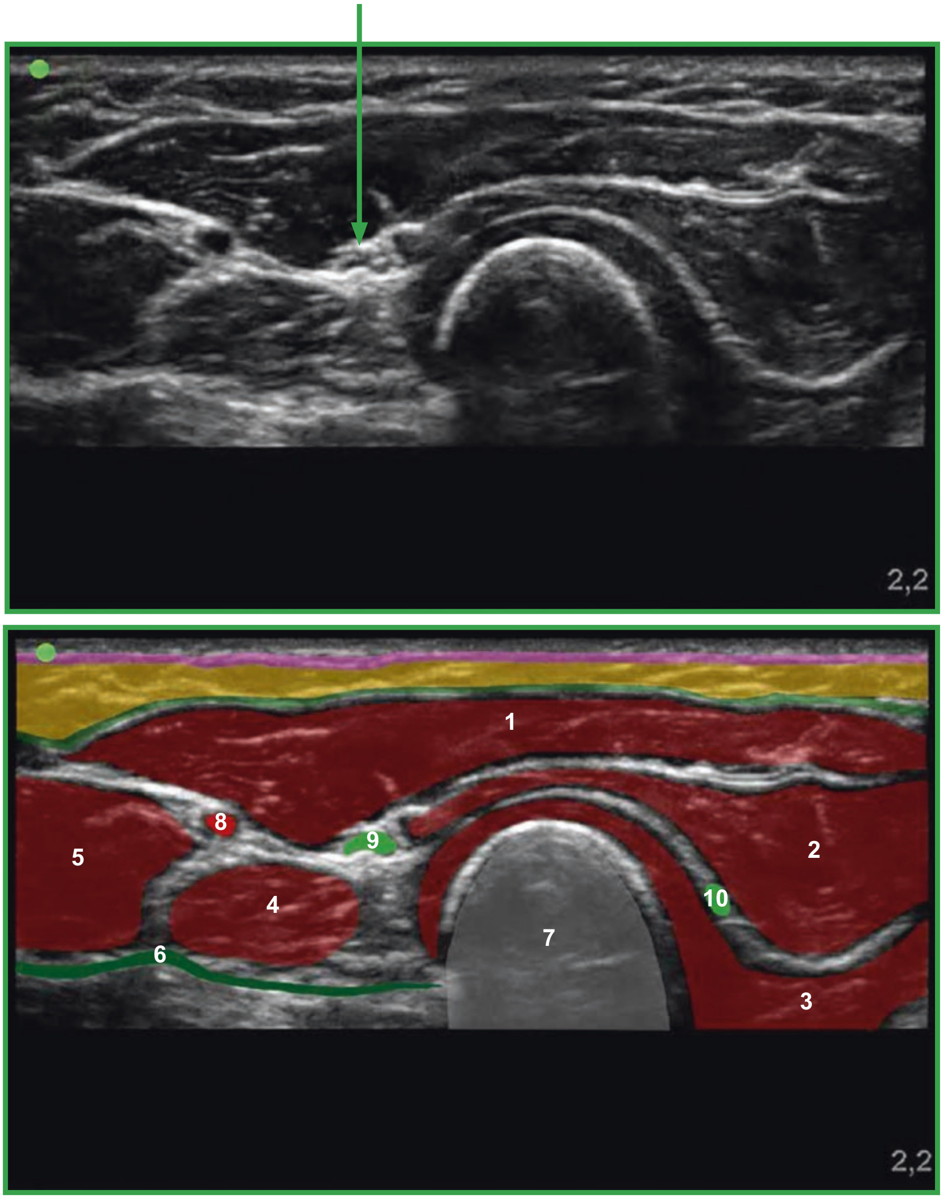


Figure R22. Ultrasound probe optimal positioning to visualize the sensitive branch of the radial nerve.



1- Brachioradialis muscle

2- Superficial head of the supinator muscle

3- Deep head of the supinator muscle

4- Flexor pollicis longus muscle

5- Flexor carpi radialis muscle

6- Interosseous membrane

7- Radius

8- Radial artery

9- Anterior sensitive branche of the radial nerve

10- Motor branche of the radial nerve

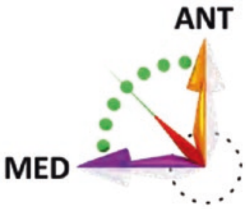


Figure R23. Ultrasound transversal views of the radial nerve sensitive branch.

Interventional Procedure

Small volume infiltrations for therapeutic and occasionally diagnostic purposes or pulsed radiofrequency on sensitive branches are possible. Low-intensity neurodetection is often necessary. Identification by clinical examination and anamnesis of the painful neuropathic territory is essential to determine the objective before performing a patient/tracking of the nerve path screening.

PNS

Neurostimulation can be performed in the sensitive branch of the radial nerve using the ultrasound scan mentioned above. The procedure for introducing the neurostimulation lead will be implemented outside the ultrasound field (out of plane), taking care to place the target in the middle of the screen and using hydrodissection and hydro-localization. The point of introduction of the needle will towards distally. At the end of the procedure, it should be visually ensured that there is at least one electrode pad in contact with the sensitive branch and one intraoperative positive sensory test, if the patient's cooperation is possible (Figure R25a). After that, the generator can be placed according to the height and weight of the patient, at the arm, infra-clavicular or axillary cavity level.

In case of neurostimulation of the superficial branch of the radial nerve, in a post-traumatic or post-surgical context, ultrasound is mainly used to avoid tendon damage, rather than actual identification of the peripheral nerves in this region (Figure R25b).

For neuropathy of the motor branch or upstream involvement, the operator can perform a C6–C7 brachial plexus SNP.

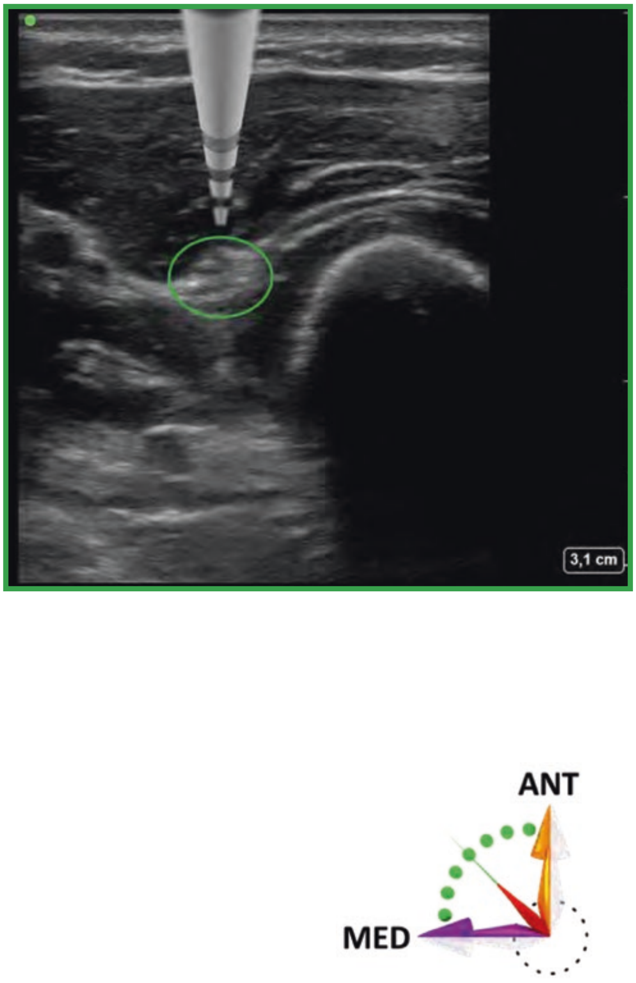


Figure R24. Ultrasound transversal views of the radial nerve to guide the introduction of the needle before lead implantation.

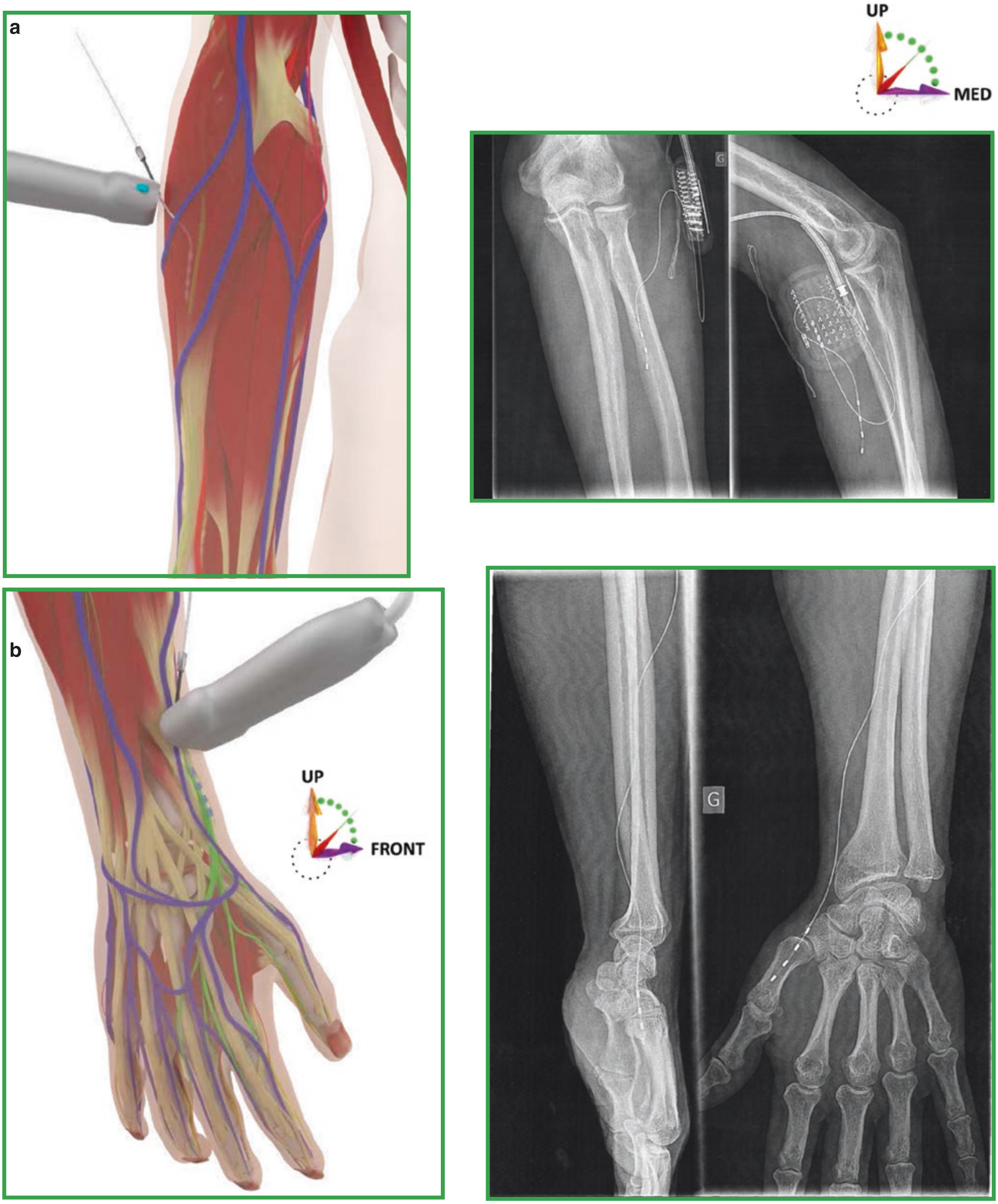


Figure R25. Some illustrative views of a peripheral nerve stimulation of the radial nerve sensitive branch. (**a**) Main sensitive branch stimulation at the junction of the distal part of the arm and forearm. (**b**) Superficial sensitive branch stimulation at the level of the anatomical snuffbox.

Surgical Procedure

Surgical Indications

- In the arm, repair of the radial nerve, particularly after direct trauma, in the context of a humeral diaphyseal fracture
- At the elbow, “posterior interosseous nerve syndrome”, in the Frohse arch

Surgical Approaches

The radial nerve can be approached along its entire path, i.e., at the arm, elbow and forearm.

On the Arm

Skin Incision

This incision starts from the posterior and lateral edge of the deltoid muscle and curves forward and laterally to the groove between the brachioradialis and brachialis muscles (Figure R26). The incision is made along the depression between the vast lateral and the long portion of the triceps.

Nervous Exposure

The fascia is then split to separate the long portion of the triceps from its vast lateral exterior and the radial nerve appears under the lower edge of the teres major muscle on the posterior surface of the arm. It is then joined by the deep brachial artery passing between the lateral and internal vastus of the triceps brachii. The nerve can be followed obliquely from inside out, in close contact at this level with the humerus in the humeral groove of the radial nerve. At this level, the different branches of motor innervation of the muscles of the posterior compartment of the arm will be found.

Once the lateral edge of the humerus is bypassed at the deep face of the lateral vastus, the radial nerve punctures the lateral intermuscular septum to penetrate the anterior compartment of the arm between the brachialis muscle inwards and the lateral leader of the triceps brachii muscle outwards. In front of the lateral intermuscular septum, the nerve will disengage the branches of the brachioradialis muscle, the extensor carpi radialis longus muscle, and the lateral part of the brachialis muscle.

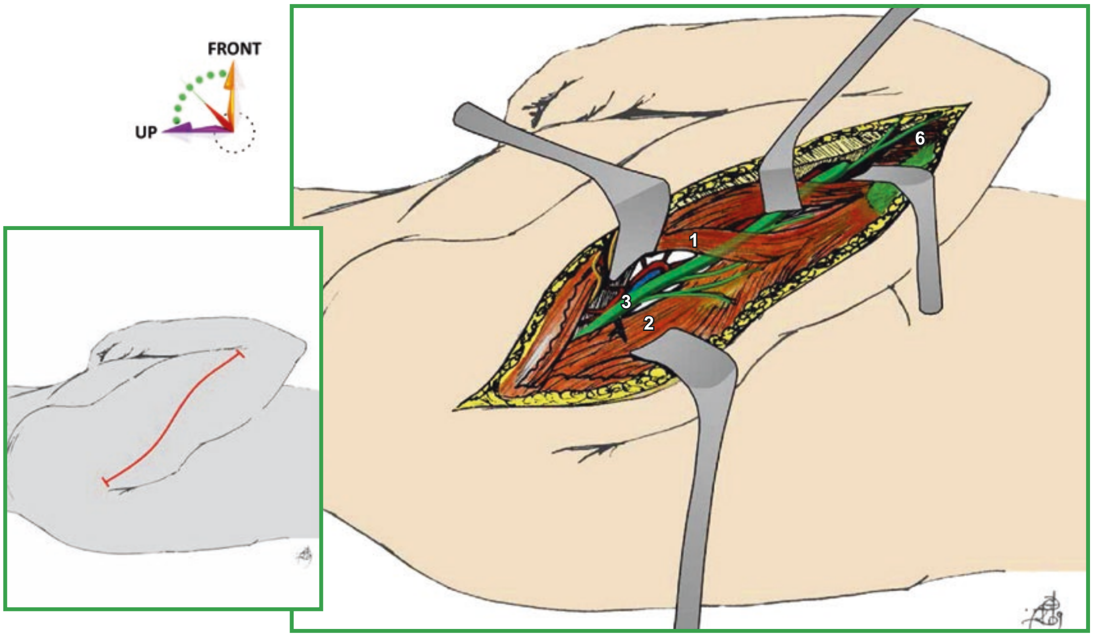
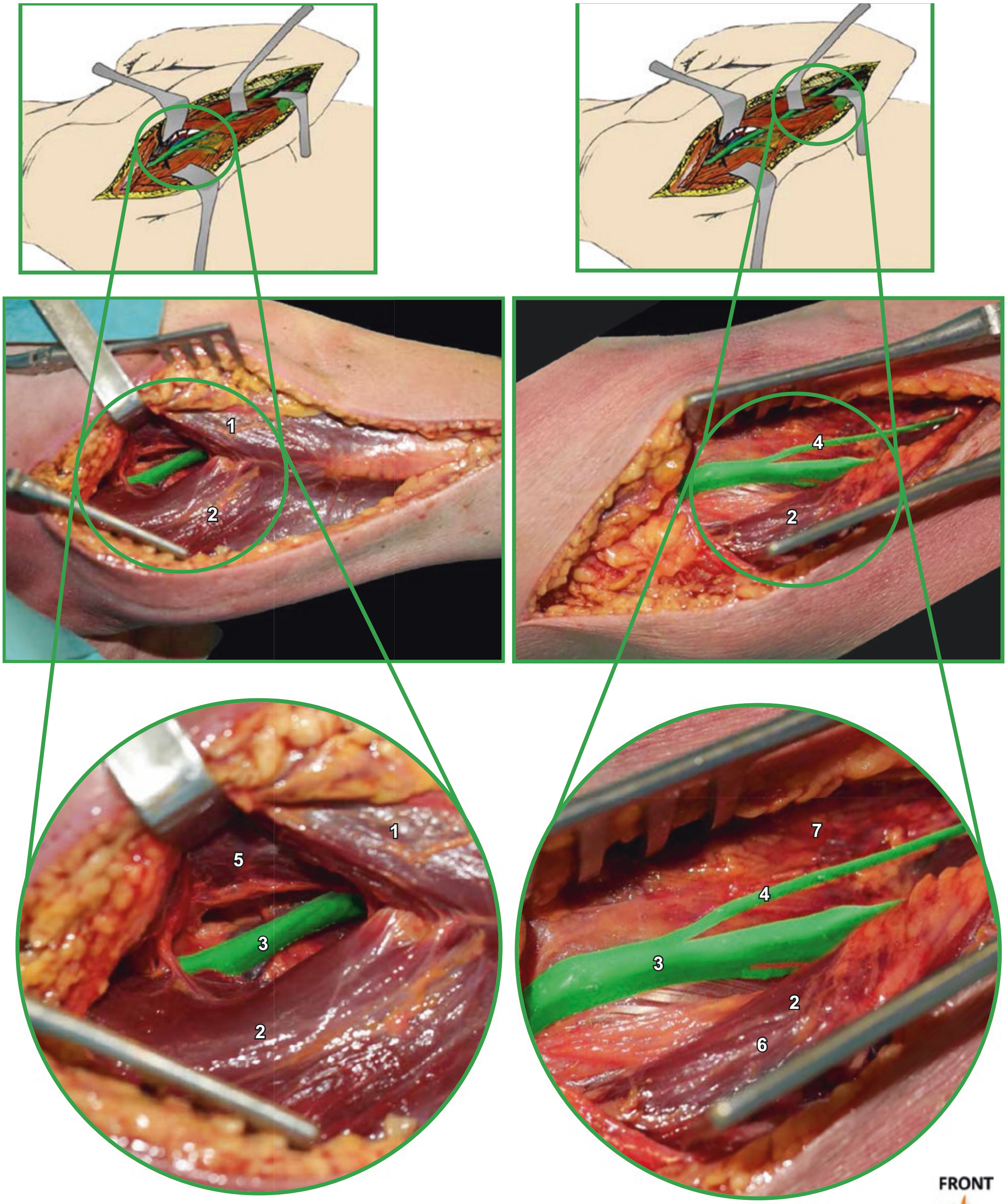


Figure R26. Surgical approach of the radial nerve at the arm level (global overview).



1- Lateral head of the triceps brachii muscle

2- Long head of the triceps brachii muscle

3- Radial nerve

4- Branch for the medial head of the triceps brachii and the anconeus muscles

5- Medial head of the triceps brachii muscle

6- Brachioradialis muscle

7- Brachialis muscle

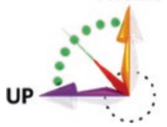


Figure R27. Surgical approach of the radial nerve at the posterior surface of the arm.

At the Elbow

Skin Incision

The incision is carried out with a hand knob above the lateral end of the elbow fold and ends along the anterior edge of the brachioradialis muscle approximately 10 cm below the elbow. It is necessary to cut the bend of the elbow horizontally to design a supinator muscle.

Nervous Exposure

The fascia is sectioned to approach the gutter between the brachioradialis muscle outside and the biceps brachii/brachialis tandem inside, at the lower and medial parts of the incision.

The pronator teres muscle can be seen inside the biceps brachii tendon.

It is necessary to respect the posterior cutaneous nerve of the forearm, perforating the fascia outside the biceps brachii. When inserted using Beckman or Farabeuf retractors, the brachioradialis muscle is found in depth and in front of the humerus, and the radial nerve in its deep region.

Shortly before its penetration into the supinator muscle, the radial nerve is generally divided into two terminal branches, anterior and posterior. The anterior branch remains superficial up to the lateral edge of the wrist, whilst the posterior motor branch passes into the posterior chamber of the forearm at the level of the Frohse arch (Figure R28) and then between the two heads of the supinator muscle. The nerve is often pre-crossed at this level by a muscular arteriolus, whilst behind it, the radial recurrent artery can be identified. The motor branch of the radial nerve can be followed (and released) by cutting off the Frohse arch and the surface fibres of the supinator muscle.

Technical Pitfalls

- Exploration of the nerve at the Frohse arch is deep, especially when patients have a well-developed brachioradialis muscle. We are almost in contact with the interosseous membrane stretched between radius and ulna. The same considerations apply to the middle third of the humerus, where it is a necessary to fetch the nerve against the bone.
- Nerve damage of the posterior cutaneous nerve of the forearm.

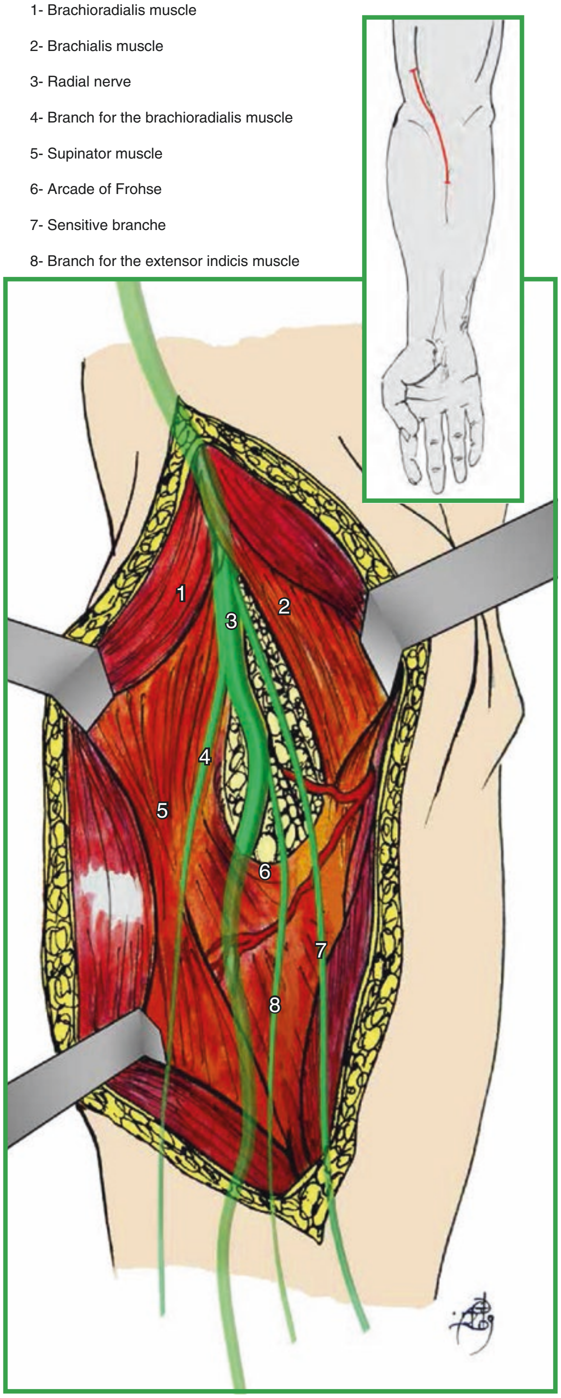

1- Brachioradialis muscle
2- Brachialis muscle
3- Radial nerve
4- Branch for the brachioradialis muscle
5- Supinator muscle
6- Arcade of Frohse
7- Sensitive branche
8- Branch for the extensor indicis muscle
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Figure R28. Surgical approach of the radial nerve at the elbow and forearm level. © Prismatics 2020. All rights reserved.

9- Extensor pollicis brevis muscle

10- Extensor pollicis longus muscle

11- Extensor carpi radialis longus muscle

12- cephalic vein

13- Dorsal metacarpal veins

14- Anterior sensitive branche of the radial nerve

15- Dorsal digital nerves of the radial nerve

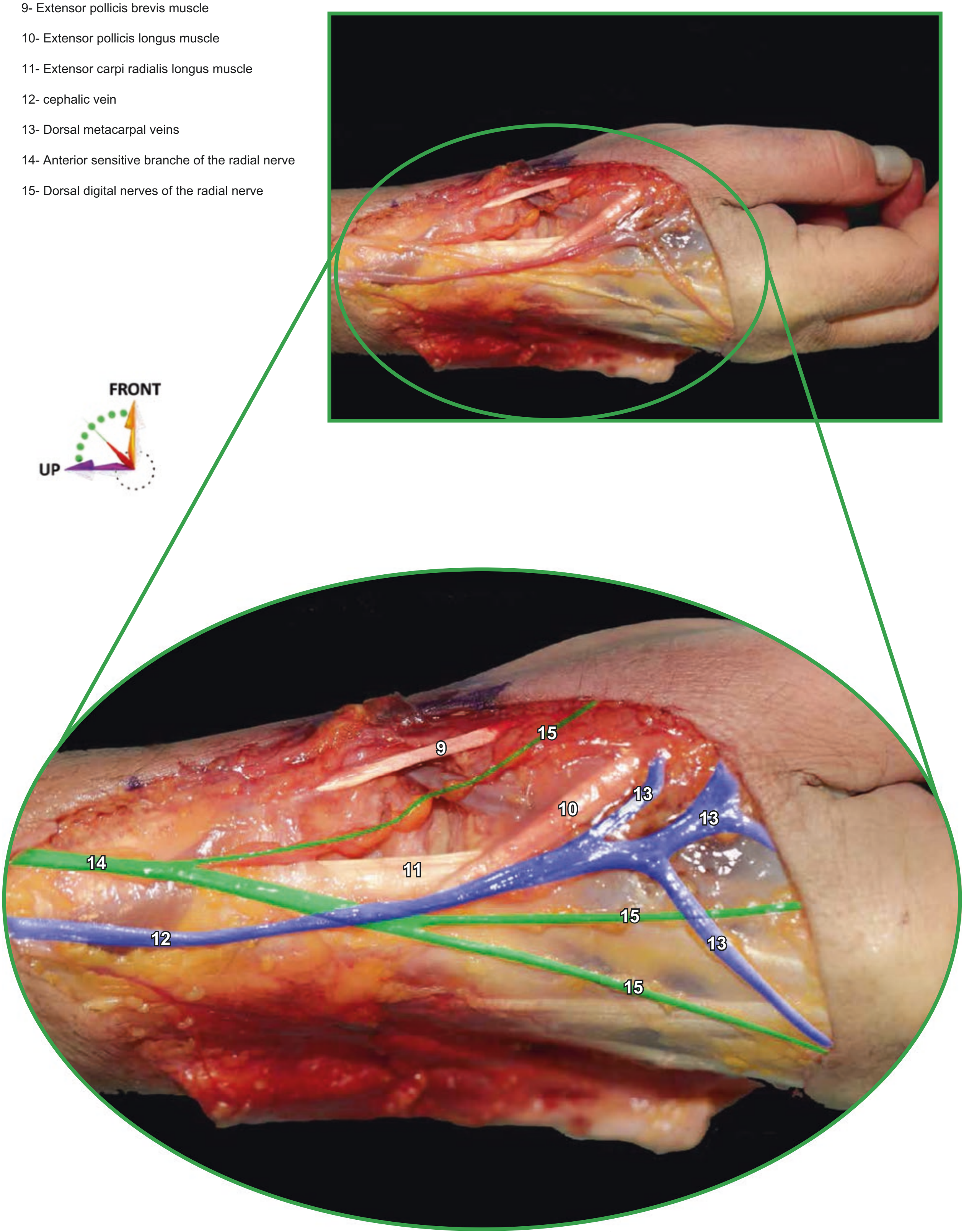


Figure R29. Surgical approach of the radial nerve at the hand level. © Prismatics 2020. All rights reserved.

The Axillary Nerve

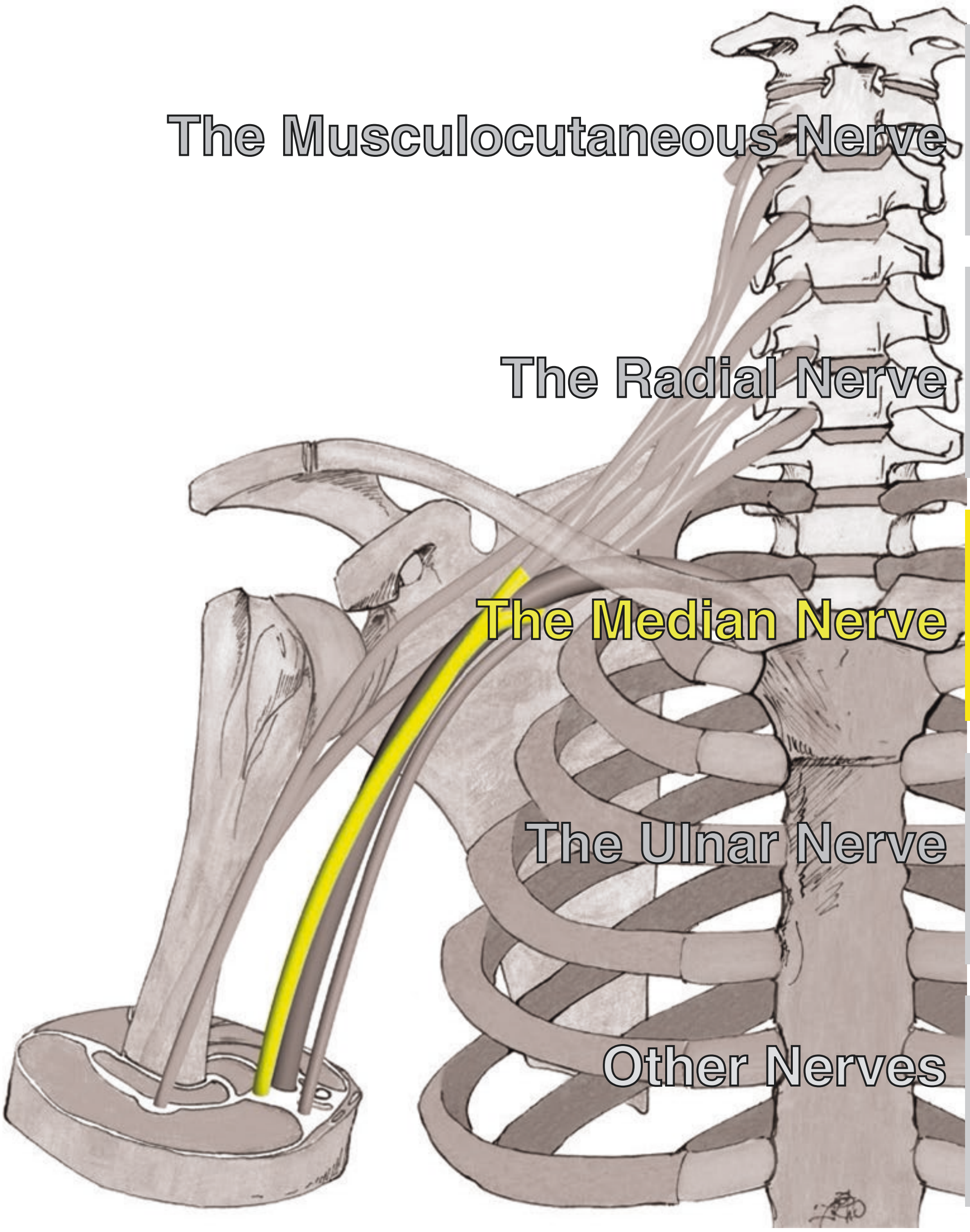
The Musculocutaneous Nerve

The Radial Nerve

The Median Nerve

The Ulnar Nerve

Other Nerves



The Median Nerve

Morphological Data

The median nerve is a mixed nerve coming from two main branches, themselves coming from the lateral and medial cords of the brachial plexus.

Origin

The median nerve is constituted of nerve fibres coming from the C6, C7, C8 and T1 roots. Sometimes, nerve fibres coming from C5 are also found (Figures M1 and M2).

The lateral cord of the brachial plexus, after giving off the musculocutaneous nerve, ends at the lateral root of the median nerve. Similarly, the medial cord, after producing the ulnar nerve and medial cutaneous nerve of the arm, ends at the medial root of the median nerve.

These two roots surround the vascular axis of the arm and then reunite at the level of its anterior and lateral face, forming a "V shape" which is situated above and outside of the musculocutaneous nerve and in front of the radial nerve (Figure M3). The terminal branches of the brachial plexus form a sheath around the axillary artery and are in close relationship with the axillary vein. The axillary artery is therefore an important landmark when performing an anaesthesia block of these nerves.

The median nerve lies in front of this artery, the ulnar and radial nerves medially and below and the musculocutaneous nerve laterally and above.

At this level, the median nerve faces the coracobrachialis muscle laterally, the pectoralis major and minor muscles in front and the subscapularis muscle in behind (Figure M3).

Path

The median nerve then goes down along the arm, lying against the brachial artery in the brachial tunnel (Figures M3 and M4). The brachial tunnel is situated in the sulcus bicipitalis medialis and is delimited by the aponeurotic expansions of the adjacent muscles: biceps brachii and coracobrachialis muscles in front and brachialis muscle behind. At this level, the median nerve is in relation with the musculocutaneous nerve laterally and the ulnar nerve and medial cutaneous nerve of the arm and of the forearm medially (Figures M12 and M14).

After crossing the brachial artery at the lower third of the arm, it places itself medially. It then goes behind the bicipital aponeurosis, lying against the brachialis muscle (Figure M5).

At the elbow, it penetrates the anterior antebrachial region by going between the two heads of the pronator teres muscle (Figure M6). When travelling through the medial axis of the forearm, it passes deeper than the flexor digitorum superficialis (Figures M7, M13, M15, M17, M18 and M19).

Three times the width of a finger above the flexor retinaculum of the hand, it emerges at the lateral edge of the flexor digitorum superficialis muscle and then penetrates into the hand through the carpal tunnel (Figures M8 and M9).

Neurovascular Relations

The median nerve faces the axillary artery behind its origin. In the arm, the median nerve laterally faces the brachial artery onto which it lies closely (Figure M3).

In the elbow, it crosses the ulnar artery from the front before entering the anterior compartment of the forearm (Figure M5).

It faces the radial artery laterally and, from a distance, behind the flexor digitorum profundus and flexor pollicis longus and also from a distance the anterior interosseous artery (Figure M7).

In the hand, the median nerve goes into the carpal tunnel where it medially faces the ulnar artery from a distance and the radial artery laterally. It then goes behind the superficial palmar arch and divides into terminal branches (Figure M10).

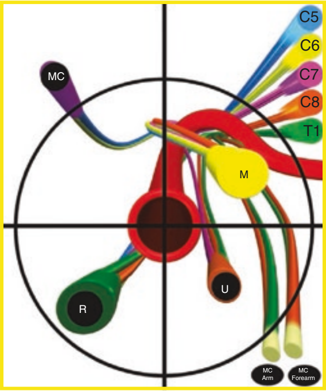


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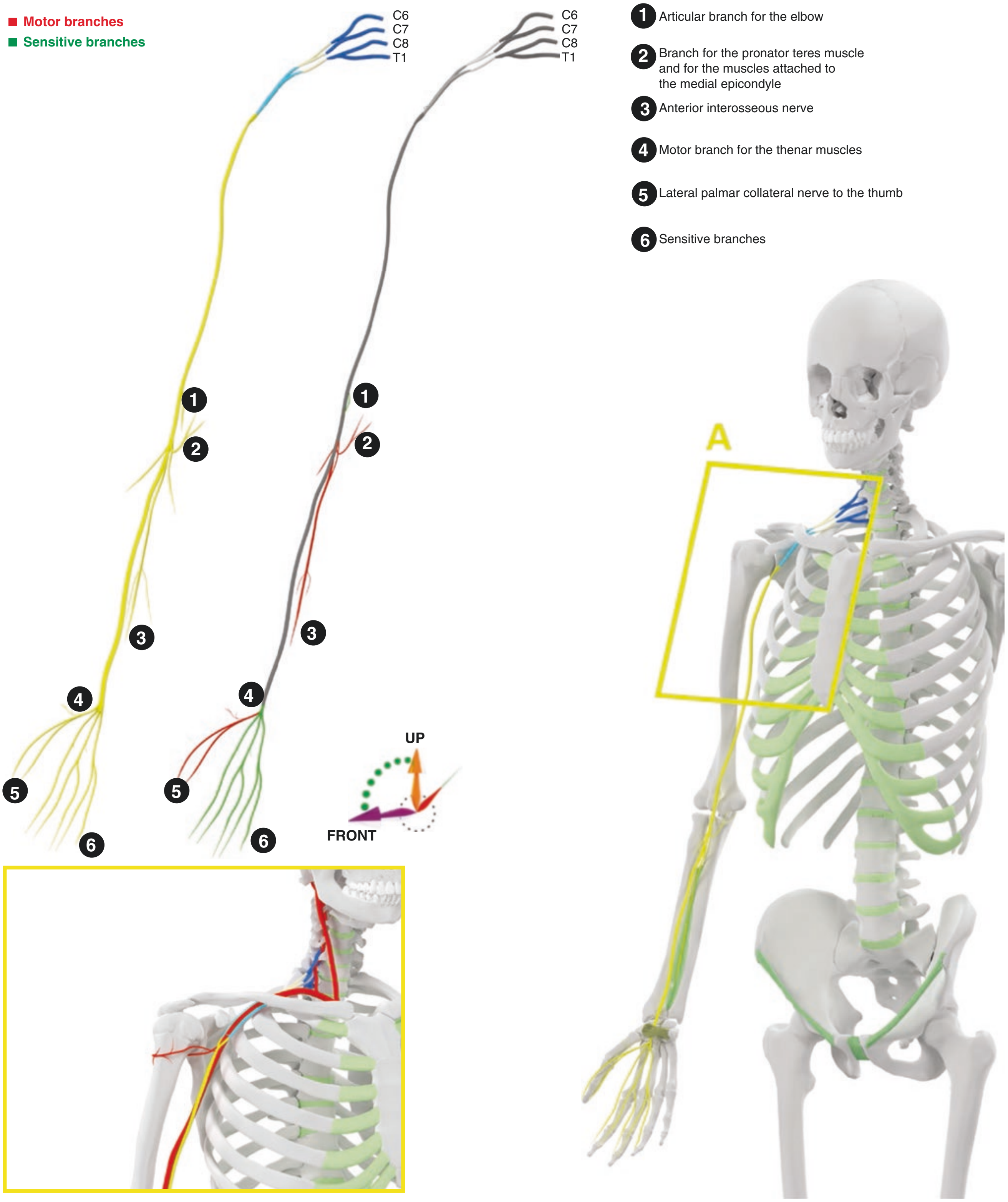
Figure M1. Origin of the median nerve.

Electronic Supplementary Material The online version of this chapter (https://doi.org/10.1007/978-3-030-49179-6_8) contains supplementary material, which is available to authorized users.


🟥 Motor branches
🟩 Sensitive branches
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1 Articular branch for the elbow

2 Branch for the pronator teres muscle and for the muscles attached to the medial epicondyle

3 Anterior interosseous nerve

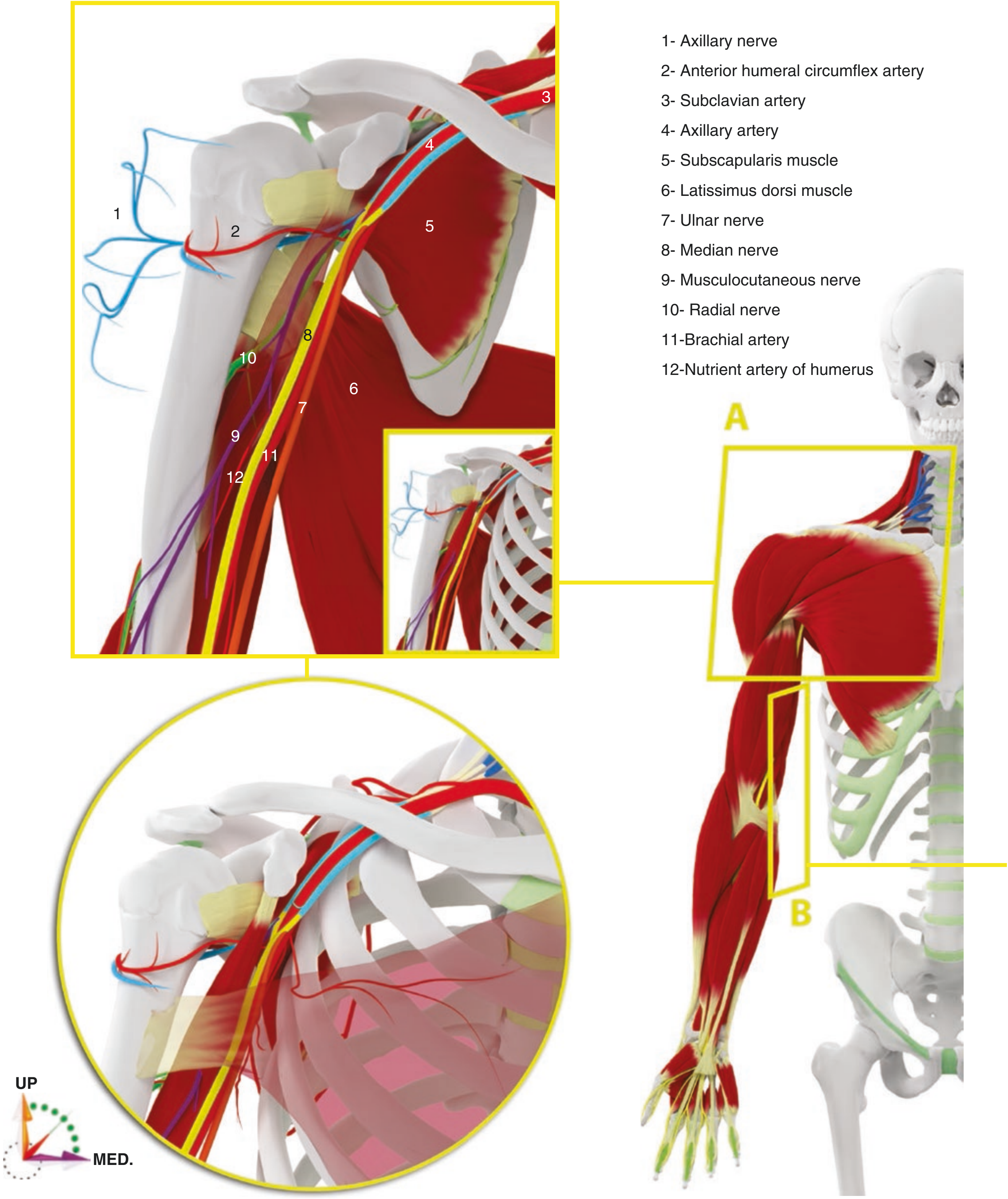
4 Motor branch for the thenar muscles

5 Lateral palmar collateral nerve to the thumb

6 Sensitive branches

Figure M2. Topographical distribution of the median nerve and its relations with bones.

The Median Nerve



1- Axillary nerve
2- Anterior humeral circumflex artery
3- Subclavian artery
4- Axillary artery
5- Subscapularis muscle
6- Latissimus dorsi muscle
7- Ulnar nerve
8- Median nerve
9- Musculocutaneous nerve
10- Radial nerve
11-Brachial artery
12-Nutrient artery of humerus

Figure M3. Path and neurovascular relations of the median nerve in the arm.

1- Biceps brachii muscle
2- Brachialis muscle
3- Median nerve
4- Ulnar nerve
5- Medial intermuscular septum
6- Olecranon

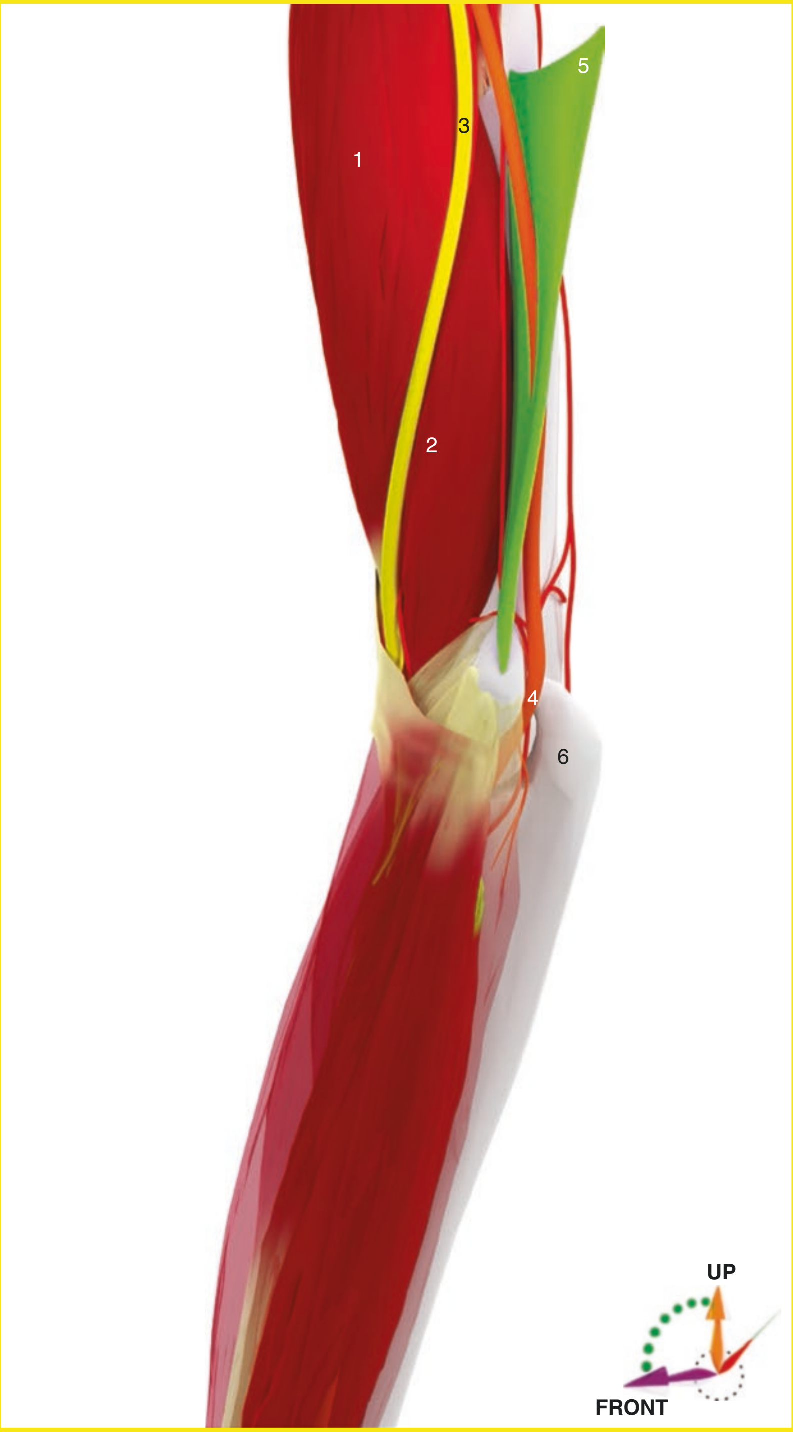


Figure M4. Path and muscular relations of the median nerve in the elbow.

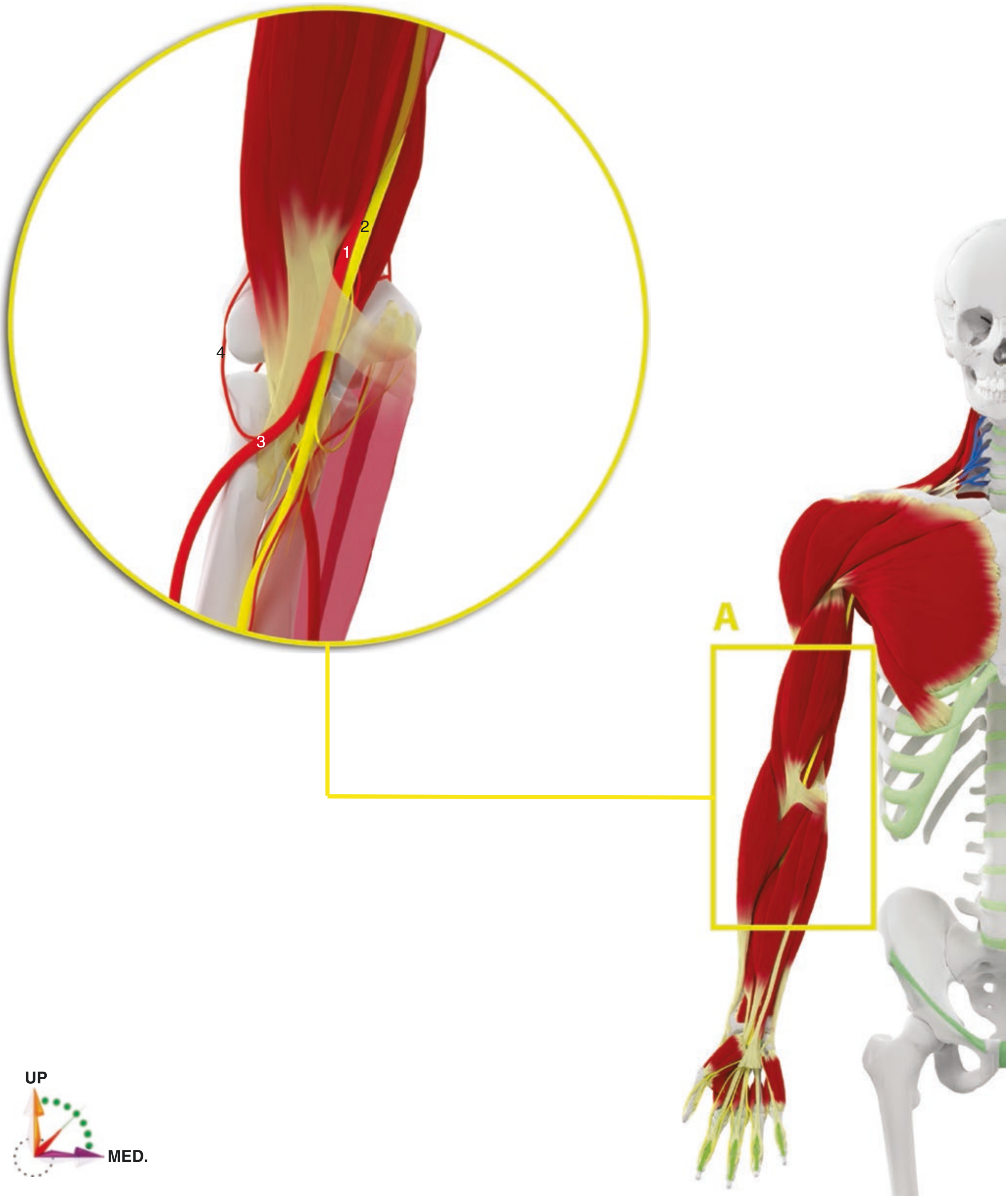


Figure M5. Neurovascular relations of the median nerve in the elbow.

1- Brachial artery
2- Median nerve
3- Radial artery
4- Radial recurrent artery
5- Brachialis muscle
6- Triceps brachii muscle
7- Brachioradialis muscle
8- Flexor pollicis longus muscle
9- Flexor digitorum profundus muscle
10- Flexor carpi ulnaris muscle
11- Pronator teres muscle
12- Flexor carpi radialis muscle
13- Palmaris longus muscle
14- Biceps brachii muscle
15- Pronator teres muscle (ulnar head)

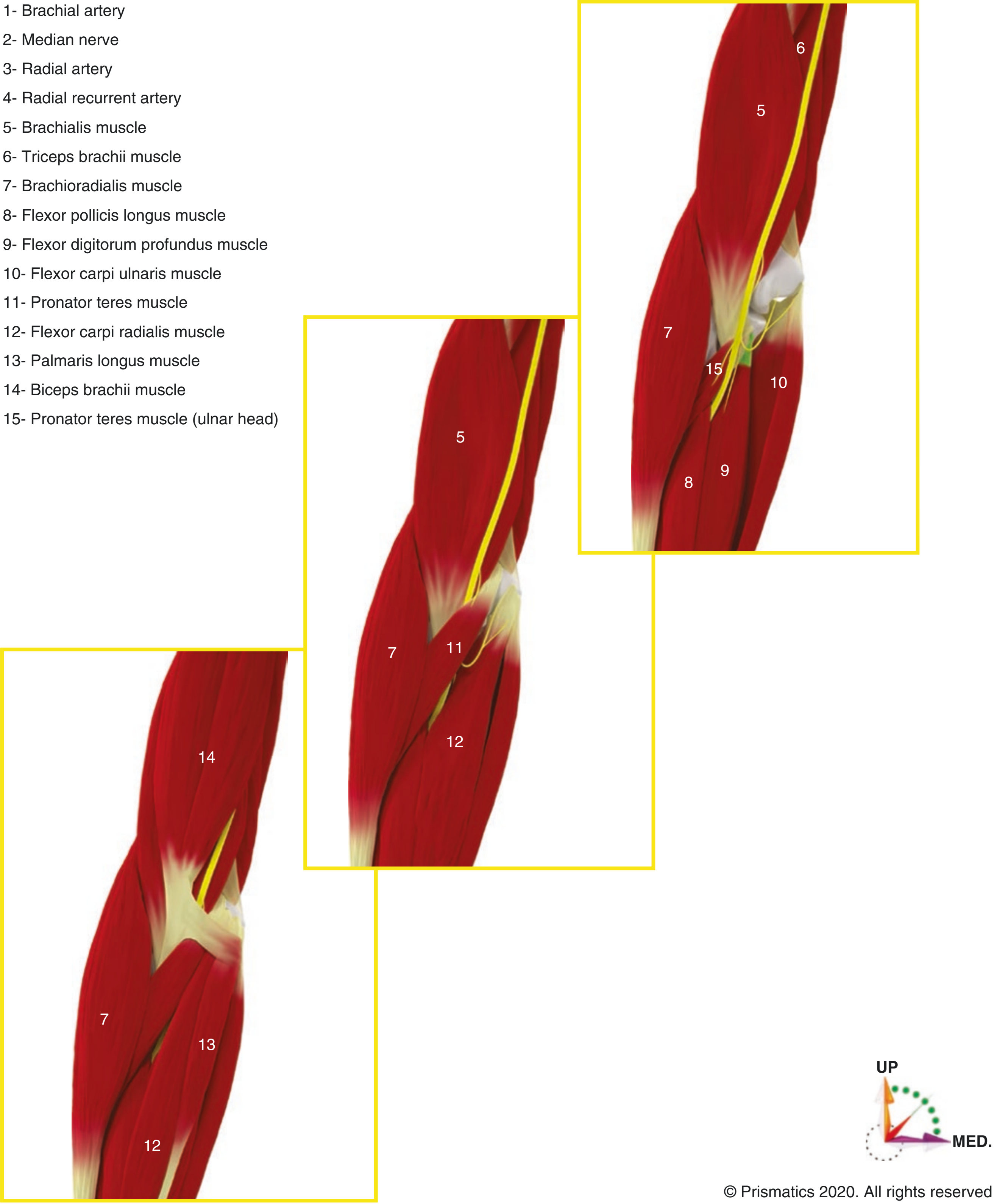
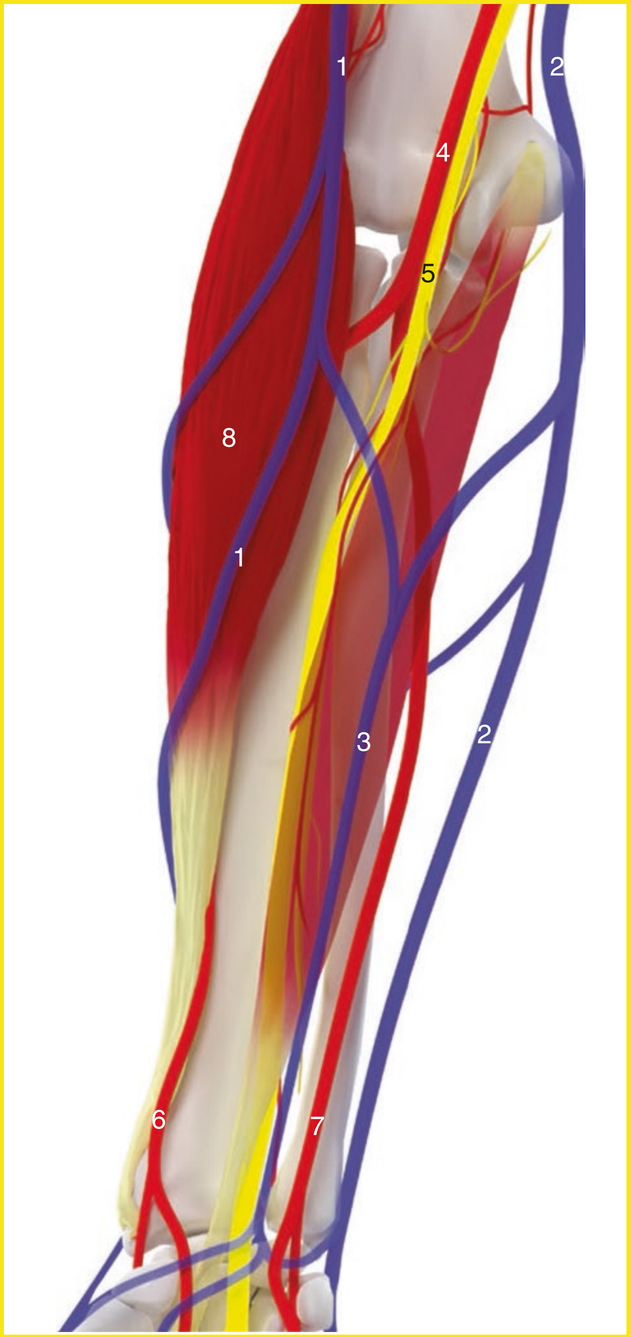
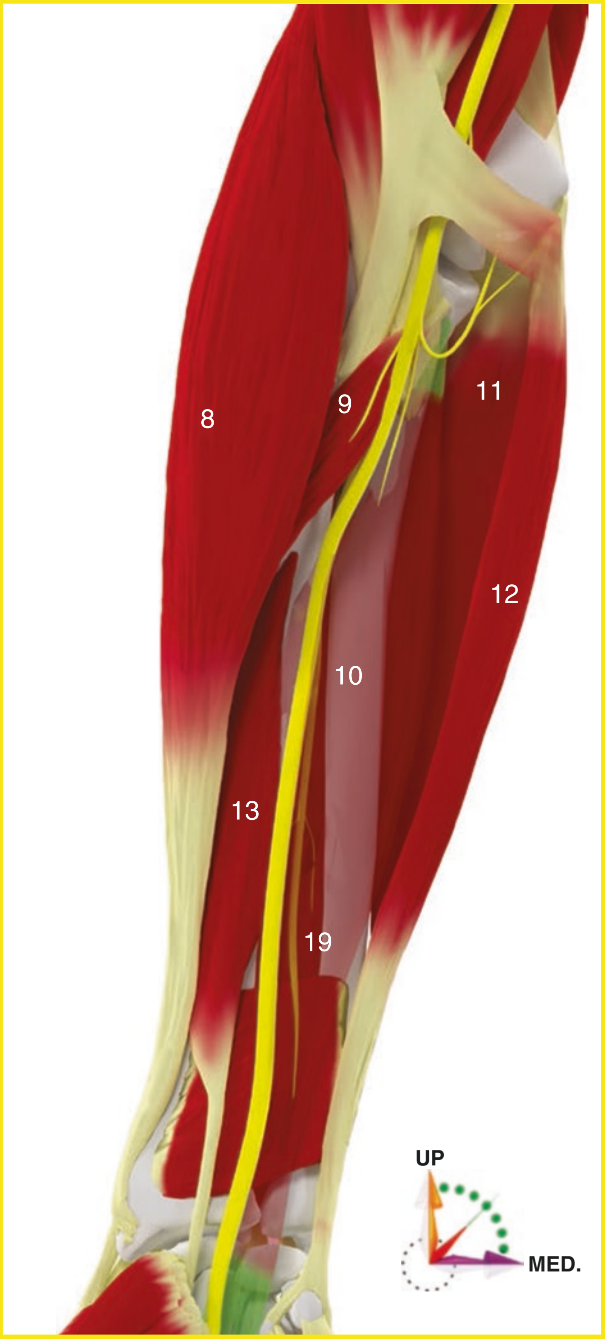


Figure M6. Muscular relations of the median nerve in the elbow.

The Median Nerve





1- Cephalic vein
2- Basilic vein
3- Median antebrachial vein
4- Brachial artery
5- Median nerve
6- Radial artery
7- Ulnar artery
8- Brachioradialis muscle
9- Pronator teres muscle (deep head)
10- Flexor digitorum profundus muscle
11- Palmaris longus muscle
12- Flexor carpi ulnaris muscle
13- Flexor pollicis longus muscle
14- Flexor carpi radialis muscle
15- Pronator teres muscle (superficial head)
16- Ulnar nerve
17- Flexor retinaculum
18- Flexor carpi radialis muscle
19- Anterior interosseous nerve (transparent view)

Figure M7. Neurovascular relations of the median nerve in the forearm.

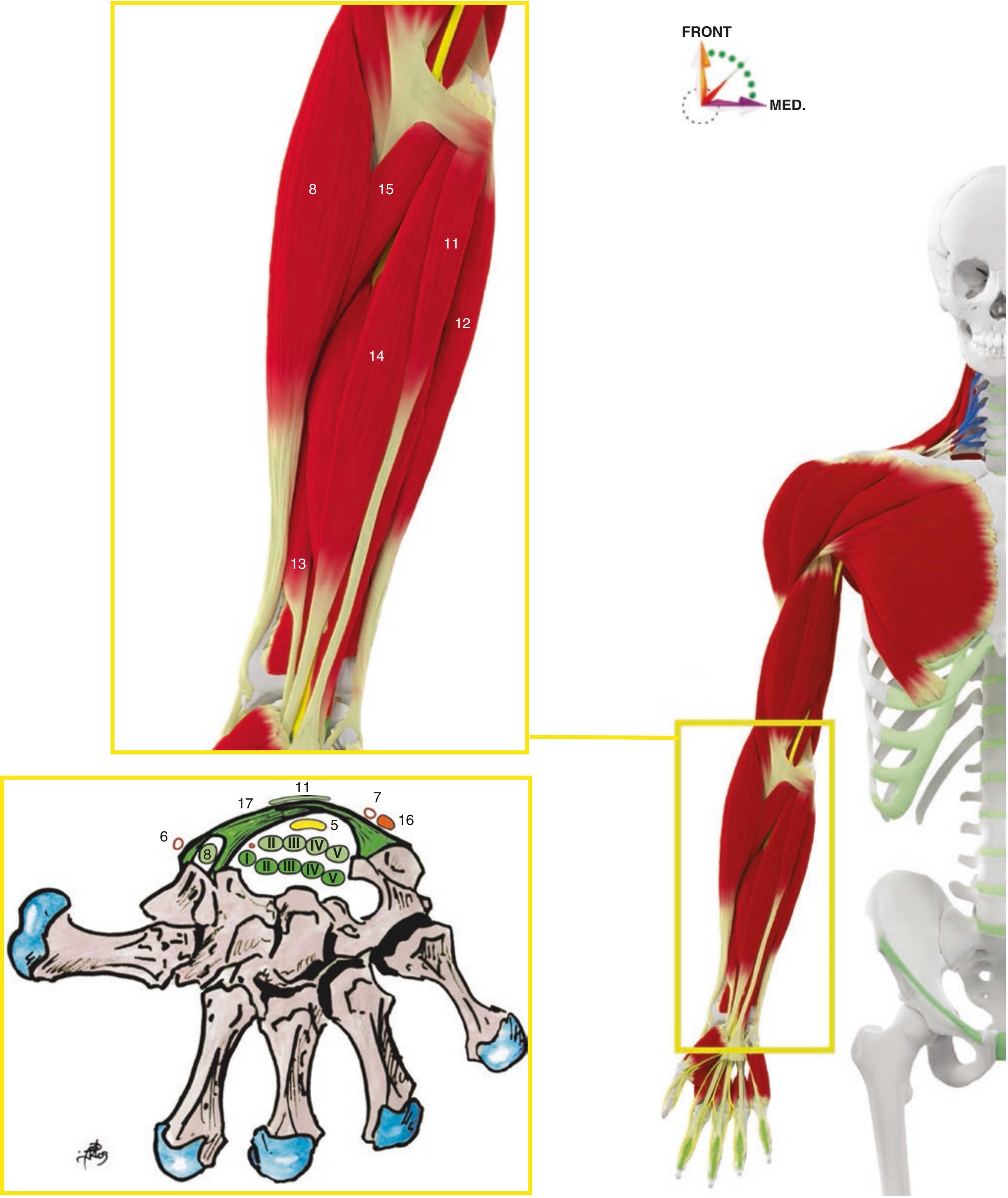

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Figure M8. Muscular relations of the median nerve in the forearm and when entering the carpal tunnel.

The Median Nerve

1- Median nerve
2- Flexor digitorum superficialis muscle
3- Abductor pollicis brevis muscle
4- Flexor pollicis brevis muscle
5- Adductor pollicis muscle
6- Lumbricals
7- Opponens digiti minimi muscle
8- Flexor digiti minimi brevis muscle
9- Abductor digiti minimi muscle
10- Flexor retinaculum
11- Common palmar digital nerve of the thumb
12- Lateral proper palmar digital nerve of the index
13- Common palmar digital nerve of the index
14- Common palmar digital nerve of the middle finger
15- Medial palmar digital nerve of the index
16- Lateral palmar digital nerve of the middle finger
17- Medial palmar digital nerve of the middle finger
18- Lateral palmar digital nerve of the ring finger

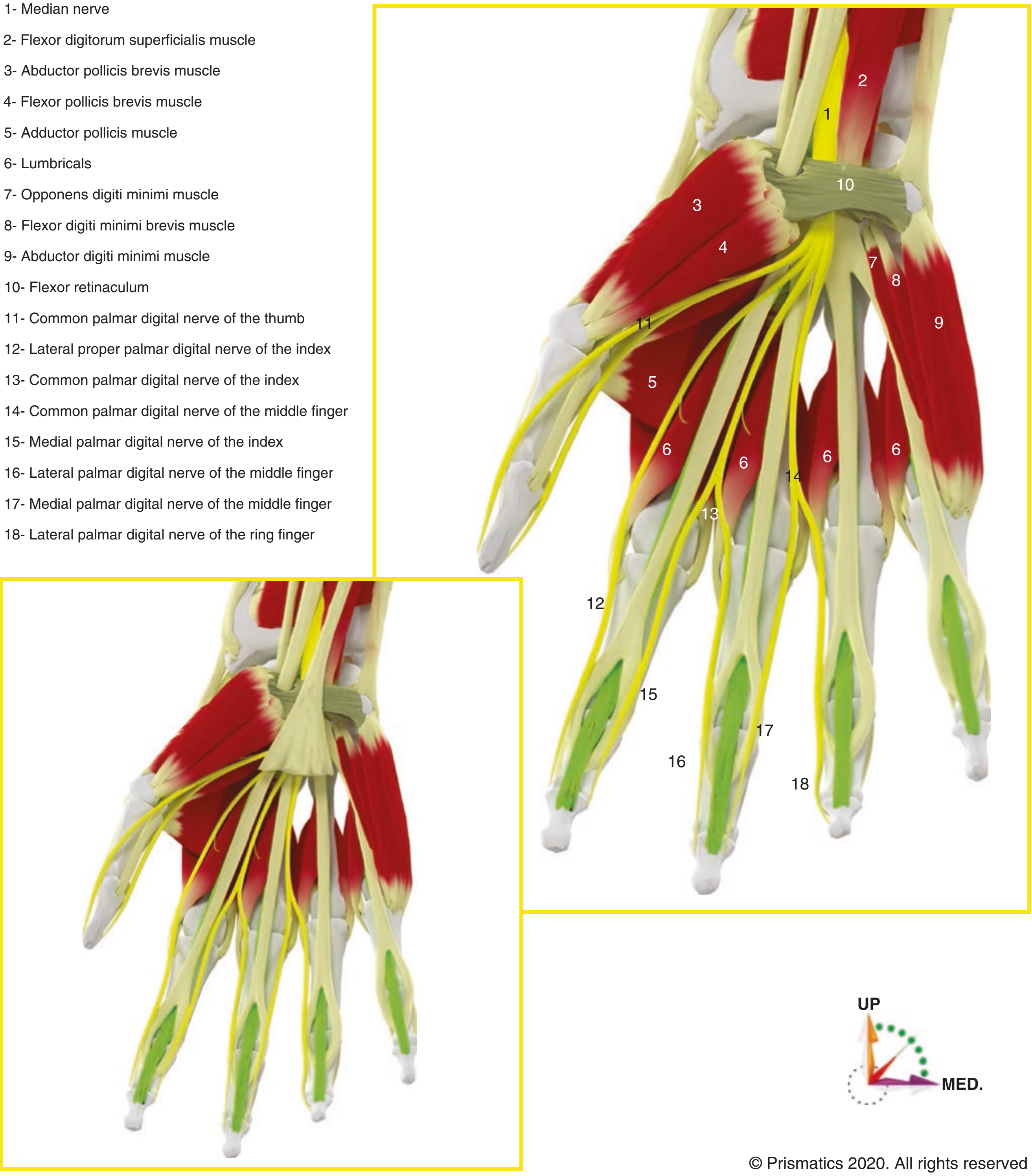
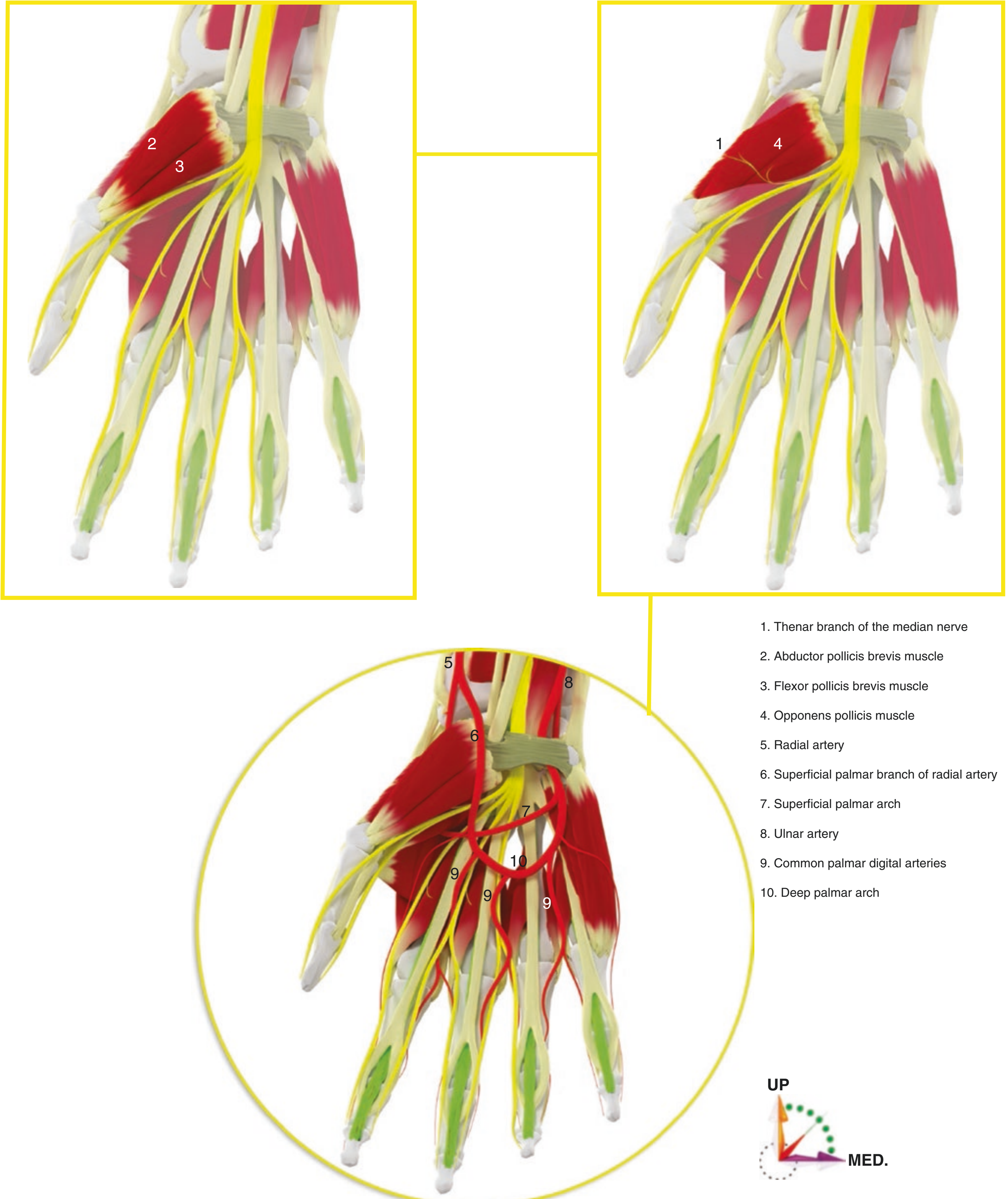


Figure M9. Relations of the median nerve in the hand.



1. Thenar branch of the median nerve
2. Abductor pollicis brevis muscle
3. Flexor pollicis brevis muscle
4. Opponens pollicis muscle
5. Radial artery
6. Superficial palmar branch of radial artery
7. Superficial palmar arch
8. Ulnar artery
9. Common palmar digital arteries
10. Deep palmar arch

Figure M10. Neurovascular relations of the median nerve in the hand.

The Median Nerve

Collateral Branches

In the arm, the median nerve gives rise to (Figure M2):

- A vascular ramus for the brachial artery
- A diaphyseal branch for the humerus
- Articular branches for the elbow
- Motor branches for the muscles in the anterior compartment of the forearm, especially the muscles related to the medial epicondyle: flexor carpi radialis, palmaris longus and flexor digitorum superficialis
- A palmar-sensitive branch for the skin of the thenar eminence and the palm of the hand

A few centimetres (5–8 cm) below the axillary pit, it goes between the two heads of the pronator teres muscle and gives rise to the anterior interosseous nerve (Figure M7).

The anterior interosseous nerve goes along the interosseous membrane of the two bones in the forearm, accompanied by the similarly named artery, and innervates the flexor pollicis longus, the lateral part of the flexor digitorum profundus and the pronator quadratus muscles. It also gives off proprioceptive fibres for the carpus, the radiocarpal and radioulnar joints, and ends at the level of the wrist.

Terminal Branches

The median nerve travels into the carpal tunnel, constituted in front by the carpal bones, shaped like a groove, itself closed in front by the flexor retinaculum of the wrist and covered by the prolongation of the tendon of the palmaris brevis muscle.

The median nerve is, in that area, accompanied in behind by the tendons of the flexor digitorum, surrounded by their synovial sheath. It is at this level that the nerve divides itself into its five terminal branches (Figure M9):

- The recurrent thenar branch: The nerve leaves the motor branch for the thenar muscles at a height that can vary. This branch can sometimes detach itself from the ventral side of the nerve (in 6% of the population), and in that case, it is particularly exposed. This branch is headed to the opponens pollicis and abductor brevis muscles, as well as the superficial bundle of the flexor pollicis brevis (Figure M10).
- The lateral palmar collateral nerve of the thumb meant for the sensitive innervation of the lateral face of its palmar side.
- Three sensitive cutaneous branches, called common digital nerves of the first, second and third interdigital spaces.
- These three branches each divide into two cords that innervate the edges of the corresponding palmar faces of the fingers. Each of these nerves ends by creating ramifications in the pulp of the last phalange of each corresponding digit.

Motor Function

The median nerve's muscle innervation area includes the pronator teres muscle and all the muscles of the anterior compartment of the forearm, except for the flexor carpi ulnaris muscle and the medial part of the flexor digitorum profundus.

In the hand, the median nerve is charged of the innervation of the muscles of the thenar eminence and the lumbricals of the index and middle fingers. It is therefore involved in the pronation of the hand on the forearm, the flexion of the fingers on the hand, the pollici-digital pinch and the flexion of the hand on the forearm (Figure M11).

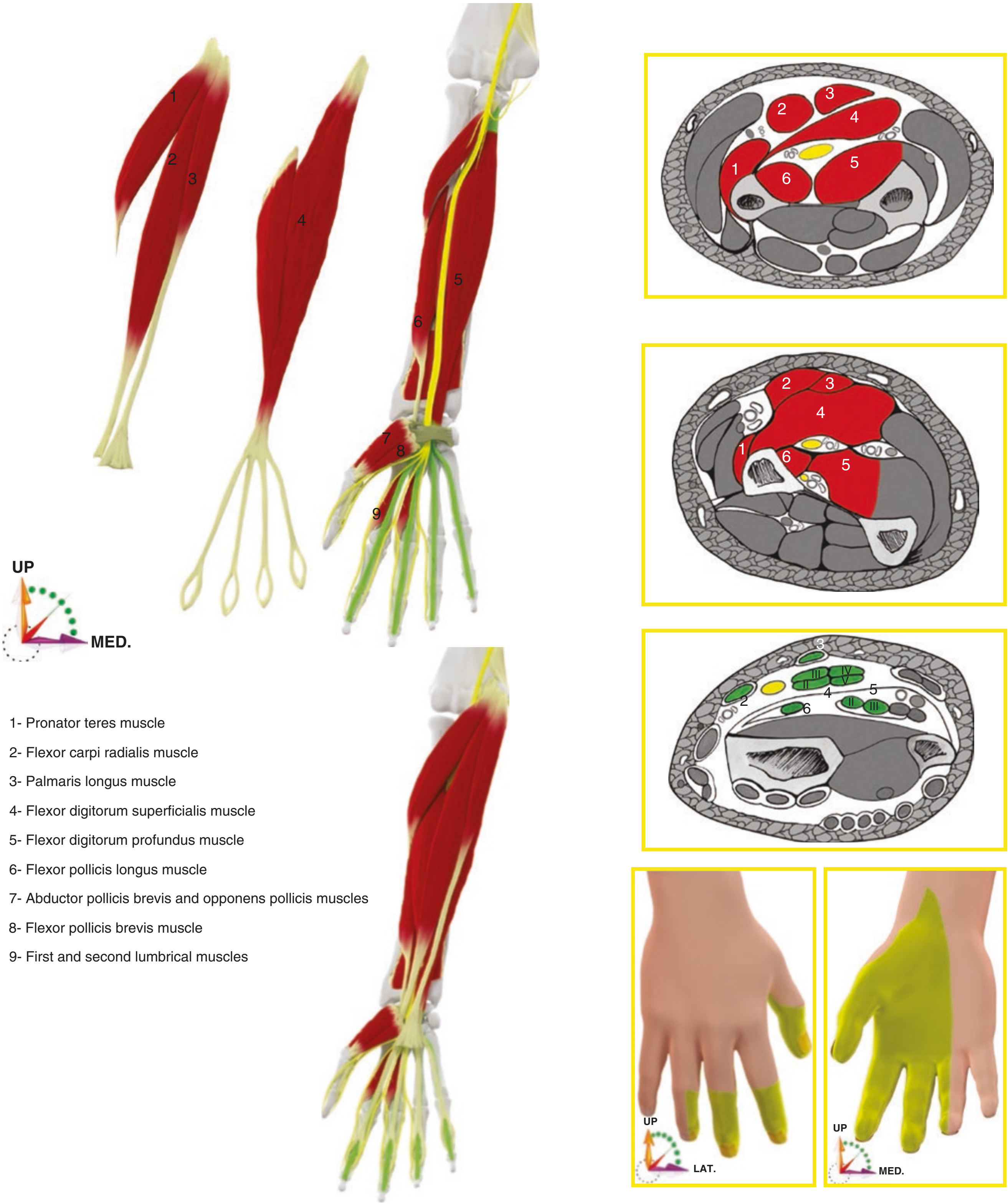
Sensitive Function

The sensitive territory of this nerve includes the whole lateral half of the palm and of the anterior face of the fingers, except for the axis going through the ring finger, in other words, the palmar faces of the first, second and third fingers and the radial half of the palmar face of the fourth finger. The posterior face corresponds to the distal and intermediate phalanges of the same fingers: first, second, third and radial half of the fourth finger (Figure M11).

Anastomoses

The median nerve produces anastomoses at different levels:

- In the arm, with the musculocutaneous nerve, described as standard by some authors of the previous century (Debierre, C. M., 1888). Likewise, anastomoses between the median nerve and the ulnar nerve seem frequent in the arm (E. Lecrosnier and Babé). This type of anastomoses can represent two or three branches between the two nerves at this level.
- In the forearm, in its superior part, with the ulnar nerve (Martin-Gruber anastomosis), between the flexor digitorum superficialis and flexor digitorum profundus. This one is often found and explains the potential substitution of the ulnar nerve for the innervation of the flexor muscles in case of a median nerve injury.
- In the hand, with the ulnar nerve (Riche-Cannieu anastomosis), at the level of the innervation of the two bundles of the flexor pollicis brevis muscle and with the radial nerve on the thenar eminence by their cutaneous ramifications.
- In the fingers, with the terminal branches of the superficial branch of the radial nerve. The anastomosis is therefore established between the collateral palmar and dorsal digital nerves.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1- Pronator teres muscle
2- Flexor carpi radialis muscle
3- Palmaris longus muscle
4- Flexor digitorum superficialis muscle
5- Flexor digitorum profundus muscle
6- Flexor pollicis longus muscle
7- Abductor pollicis brevis and opponens pollicis muscles
8- Flexor pollicis brevis muscle
9- First and second lumbrical muscles

Figure M11. Motor and sensitive innervation of the median nerve.

1- Pectoralis major muscle
2- Pectoralis minor muscle
3- Cephalic vein
4- Deltoid muscle
5- Short head of the biceps brachii muscle
6- Coracobrachialis muscle
7- Tendon of the long head of the biceps brachii muscle
8- Latissimus dorsi muscle
9- Humerus
10- Teres major muscle
11- Lateral head of the triceps brachii muscle
12- Circumflex artery and nerve
13- Long head of the triceps brachii muscle
14- Teres minor muscle
15- Infraspinatus muscle
16- Scapula
17- Medial cutaneous nerve of arm
18- Median nerve
19- Medial cutaneous nerve of forearm
20- Ulnar nerve
21- Radial nerve
22- Musculocutaneous nerve
23- Subscapularis muscle
24- Brachial vein
25- Brachial artery
26- Serratus anterior muscle
27- Biceps brachii muscle
28- Brachialis muscle
29- Brachioradialis muscle

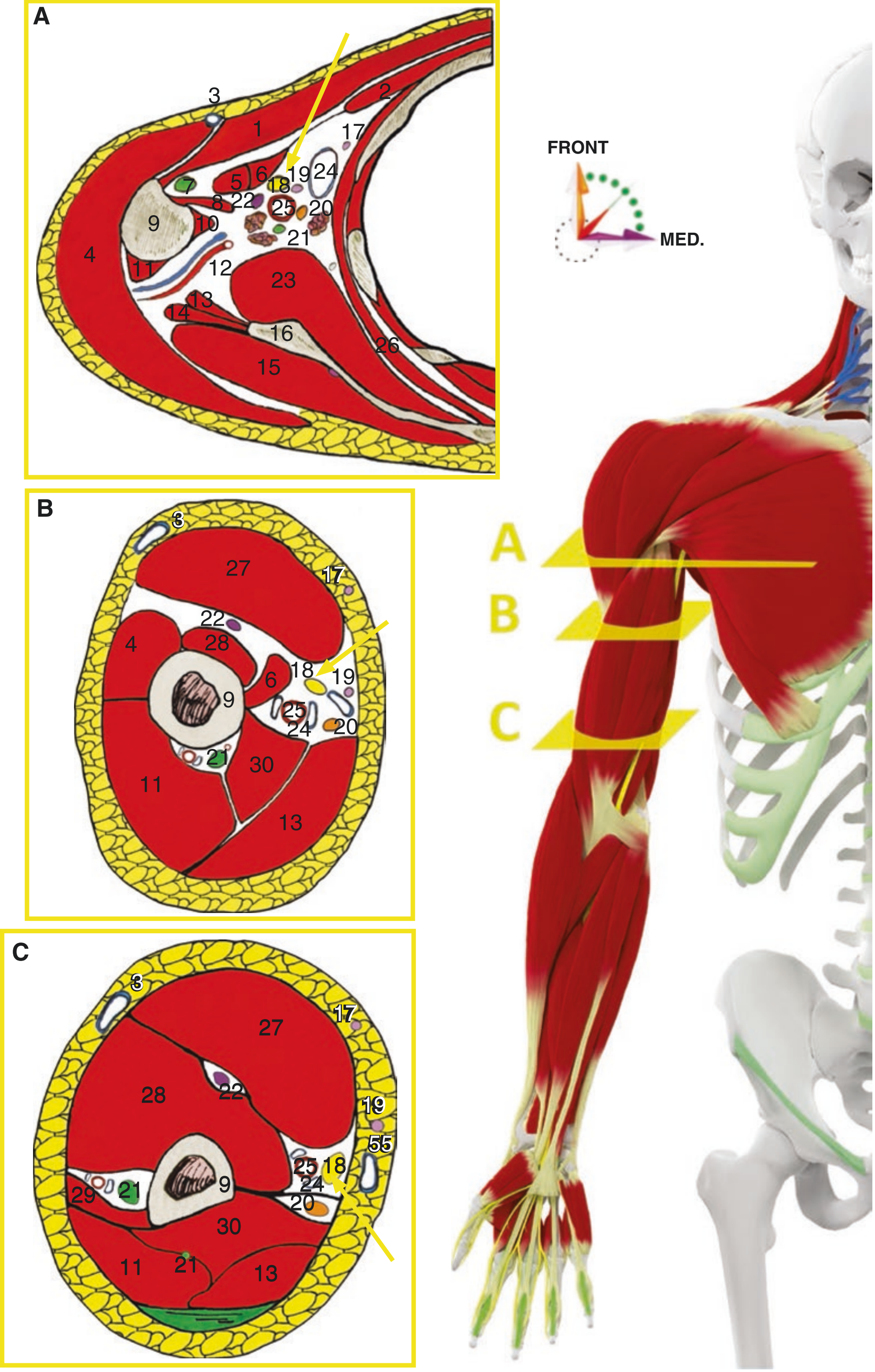
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Figure M12. Relations of the median nerve in the arm, axial sections.

30- Medial head of the triceps brachii muscle

31- Extensor carpi radialis longus muscle

32- Extensor carpi radialis brevis muscle

33- Tendon of epicondyle muscles

34- Anconeus muscle

35- Olecranon

36- Tendon of the triceps brachii muscle

37- Tendon of the median epycondylian muscles

38- Pronator teres muscel

39- Ulna

40- Radius

41- Palmaris longus muscle

42- Flexor carpi radialis muscle

43- Flexor digitorum superficialis muscle

44- Flexor digitorum profundus muscle

45- Flexor pollicis longus muscle

46- Flexor carpi ulnaris muscle

47- Abductor pollicis longus muscle

48- Extensor pollicis brevis muscle

49- Extensor pollicis longus muscle

50- Extensor digitorum muscle

51- Extensor digiti minimi muscle

52- Extensor carpi ulnaris muscle

53- Extensor indicis muscle

54- Median vein of the forearm

55- Basilic vein

56- Radial artery and vein

57- Ulnar artery and vein

58- Pronator quadratus muscle

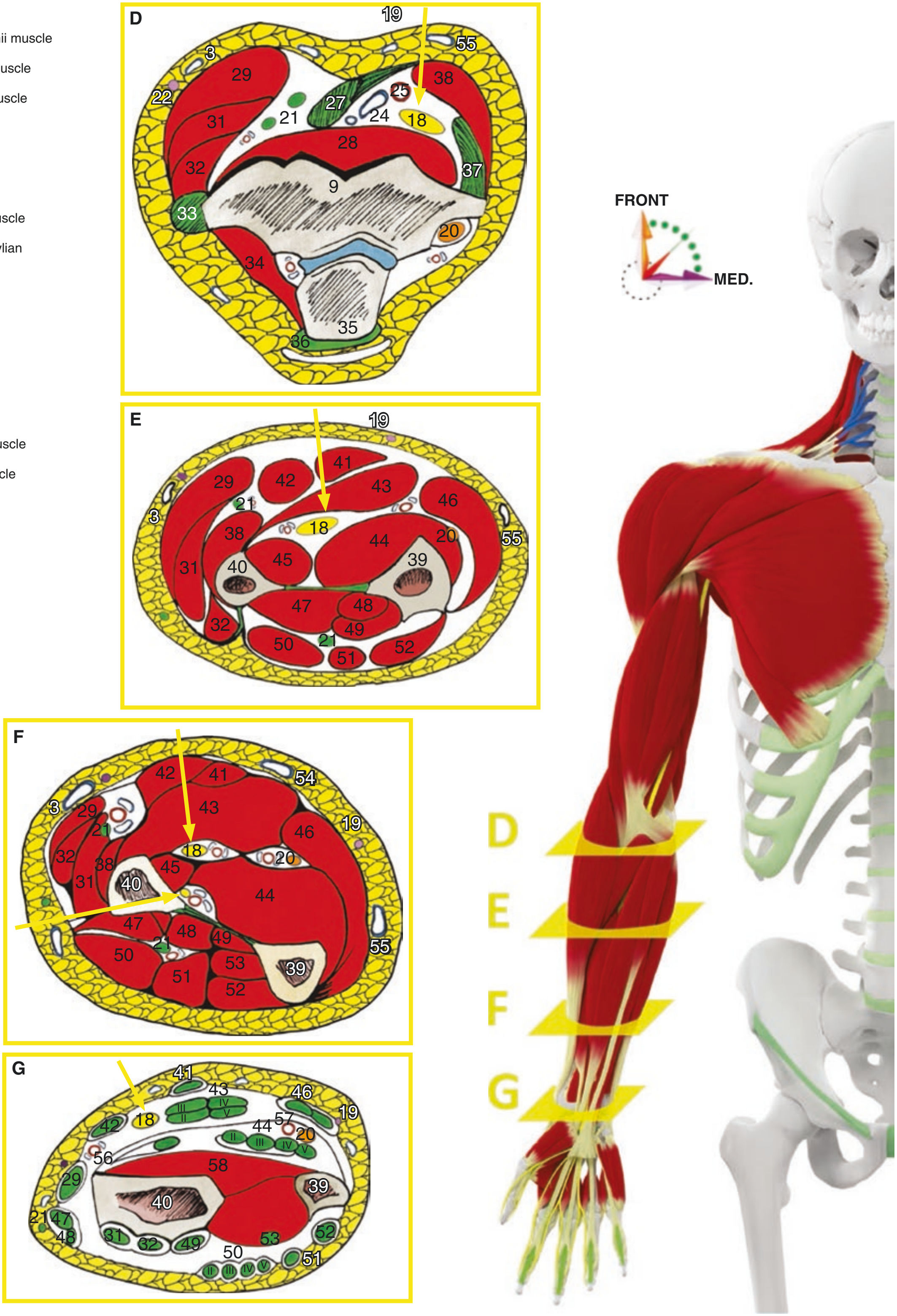
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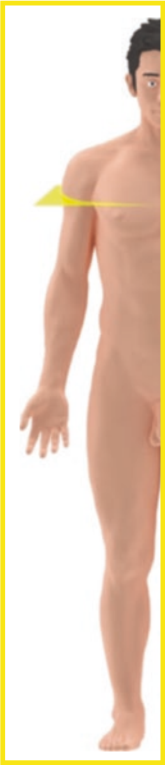
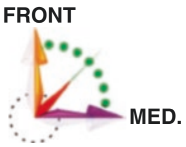
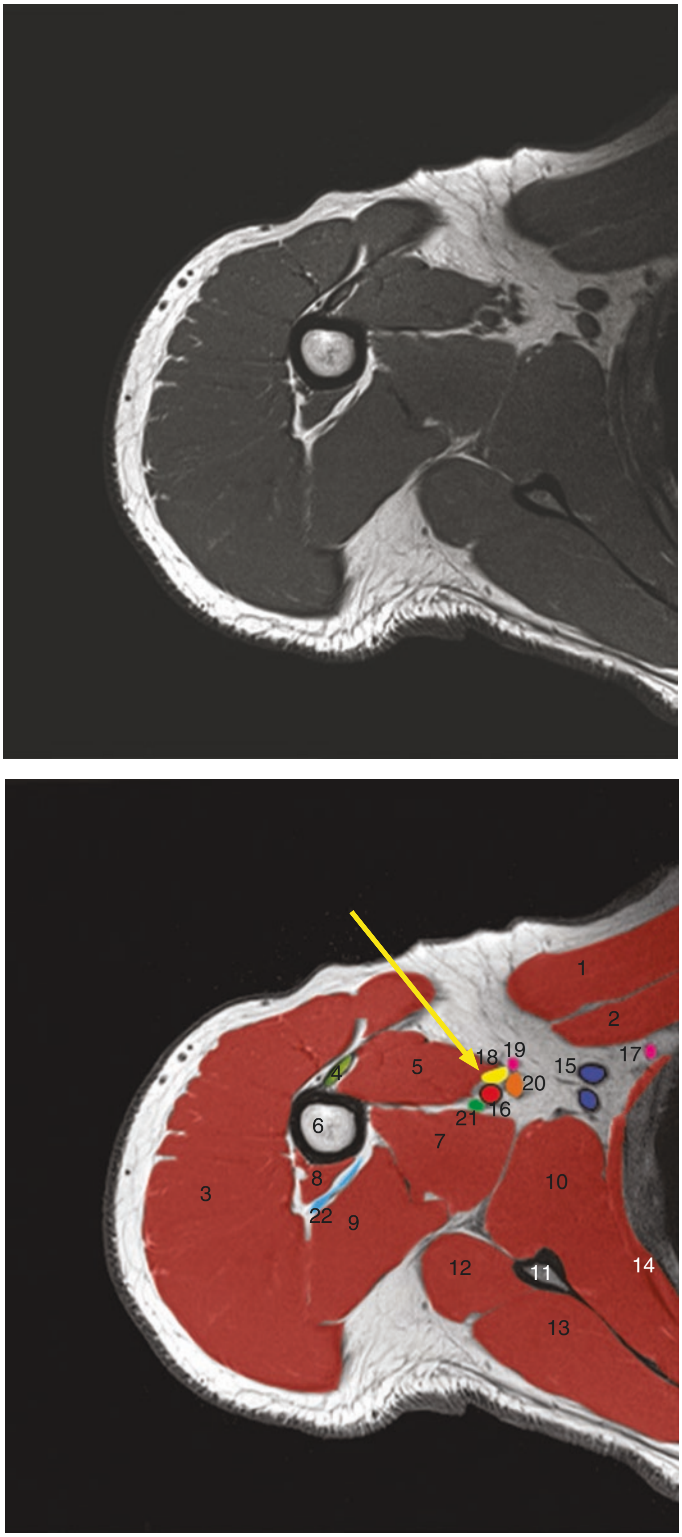
Figure M13. Relations of the median nerve in the elbow and forearm, axial sections.

The Median Nerve

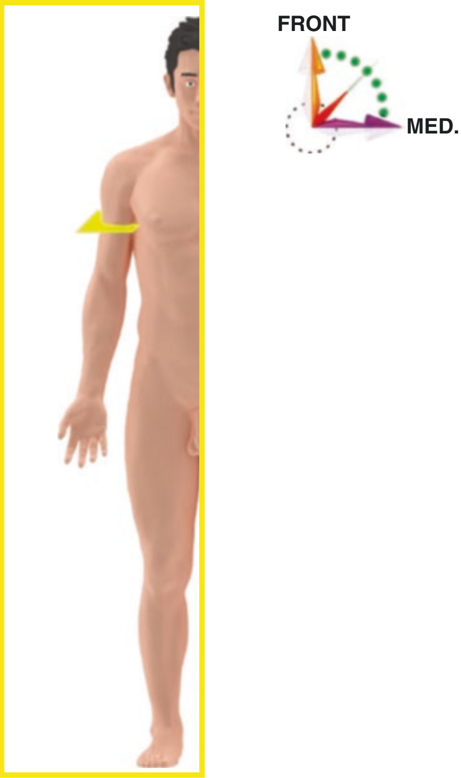


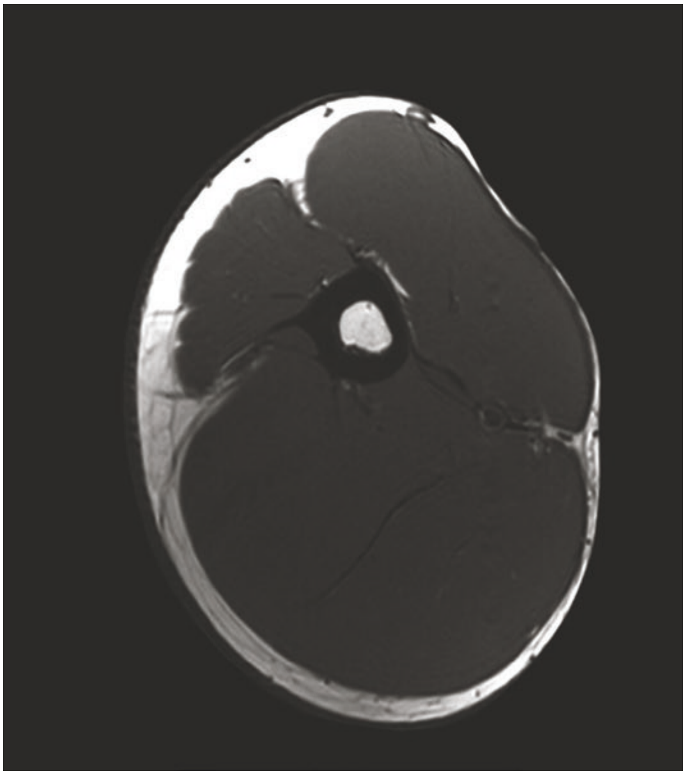


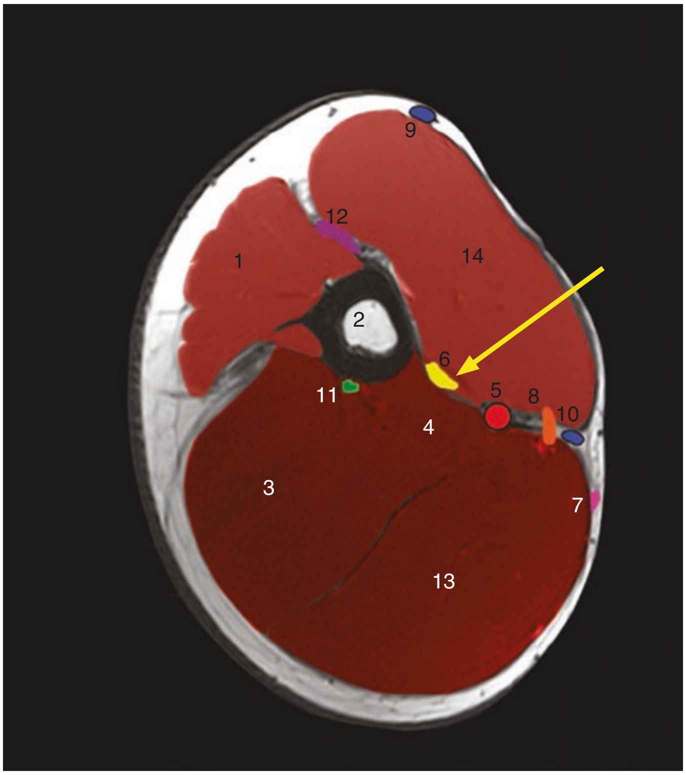


1- Pectoralis major muscle
2- Pectoralis minor muscle
3- Deltoid muscle
4- Long head of the biceps brachii muscle
5- Latissimus dorsi muscle
6- Humerus
7- Teres major muscle
8- Lateral head of the triceps brachii muscle
9- Medial head of the triceps brachii muscle
10- Subscapularis muscle
11- Scapula
12- Teres minor muscle
13- Infraspinatus muscle
14- Serratus anterior
15- Brachial vein
16- Brachial artery
17- Medial cutaneous nerve of arm
18- Median nerve
19- Medial cutaneous nerve of forearm
20- Ulnar nerve
21- Radial nerve
22- Axillary nerve

Figure M14. MRI scans in the shoulder through the median nerve.







1- Deltoid muscle

2- Humerus

3- Lateral head of the triceps brachii muscle

4- Medial head of the triceps brachii muscle

5- Brachial artery

6- Median nerve

7- Medial cutaneous nerve of forearm

8- Ulnar nerve

9- Cephalic vein

10- Basilic vein

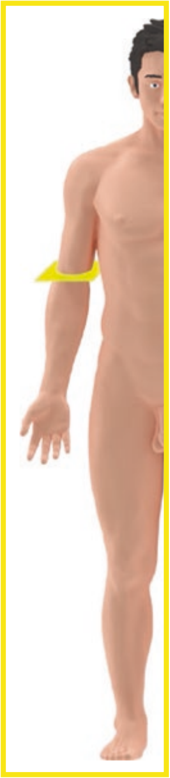
11- Radial nerve

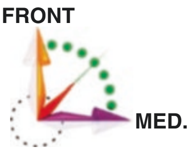
12- Musculocutaneous nerve

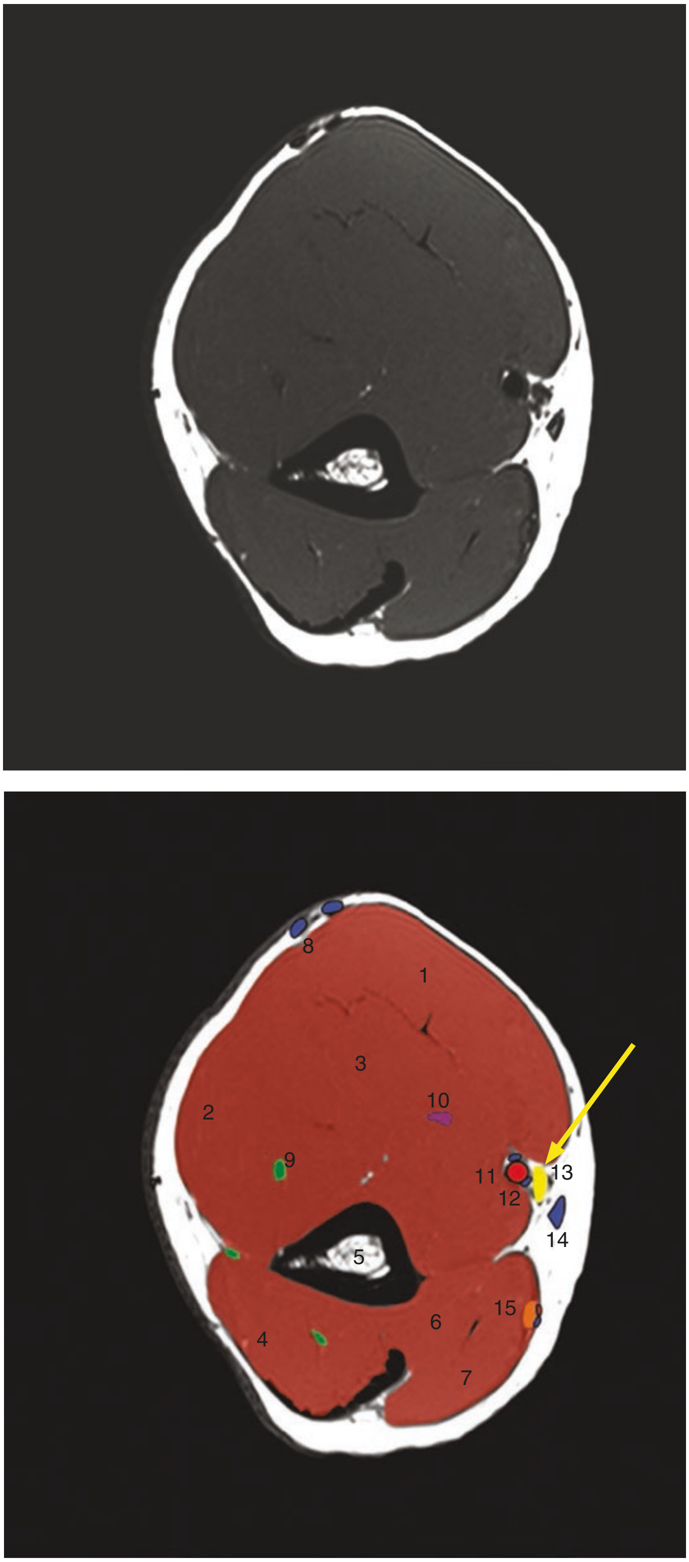
13- Long head of the triceps brachii muscle

14- Biceps brachii muscle

Figure M15. MRI scans at the proximal third of the arm through the median nerve.

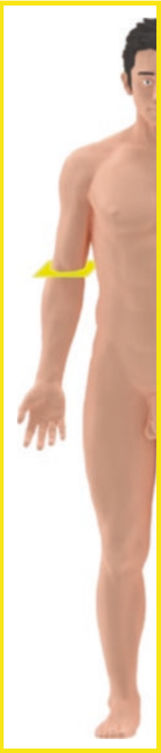


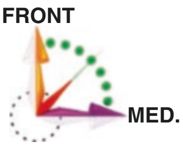


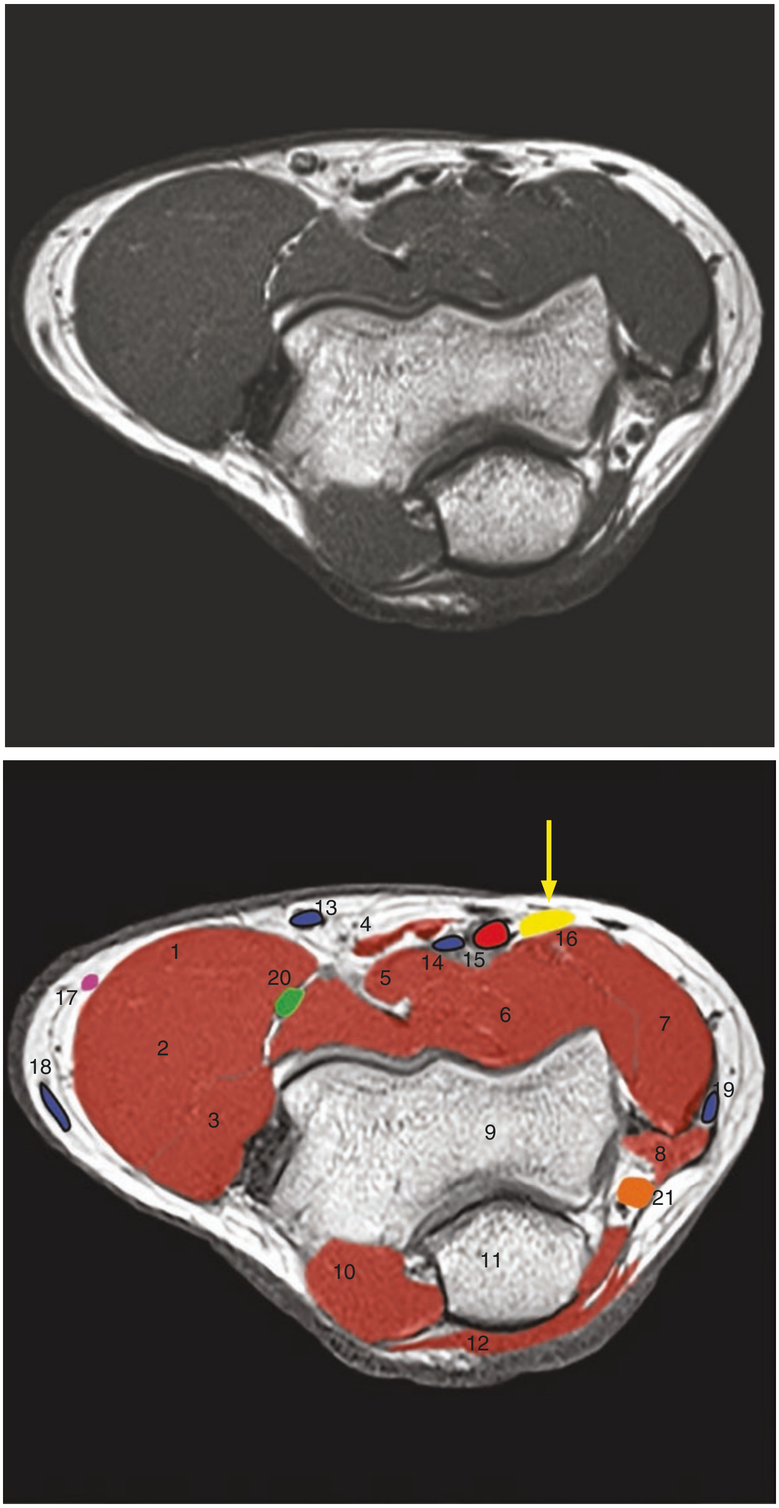


1- Biceps brachii muscle
2- Brachioradialis muscle
3- Brachialis muscle
4- Lateral head of the triceps brachii muscle
5- Humerus
6- Long head of the triceps brachii muscle
7- Medial head of the triceps brachii muscle
8- Cephalic vein
9- Radial nerve
10- Musculocutaneous nerve
11- Brachial artery
12- Brachial vein
13- Median nerve
14- Basilic vein
15- Ulnar nerve

Figure M16. MRI scans at the distal third of the arm through the median nerve.







1- Brachioradialis muscle

2- Extensor carpi radialis longus muscle

3- Extensor carpi radialis brevis muscle

4- Biceps brachii muscle

5- Tendon of the long head of biceps

6- Brachialis muscle

7- Pronator teres muscle

8- Tendon of the medial epicondylian muscles

9- Humerus

10- Anconeus muscle

11- Ulna

12- Triceps brachii muscle

13- Medial vein at the elbow

14- Brachial vein

15- Brachial artery

16- Median nerve

17- Musculocutaneous nerve

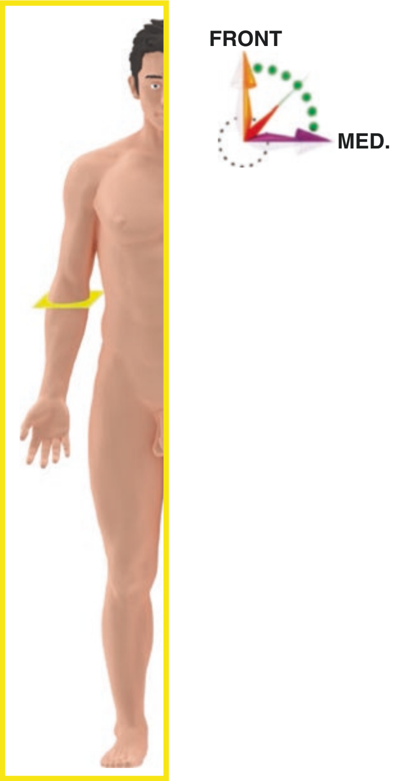
18- Cephalic vein

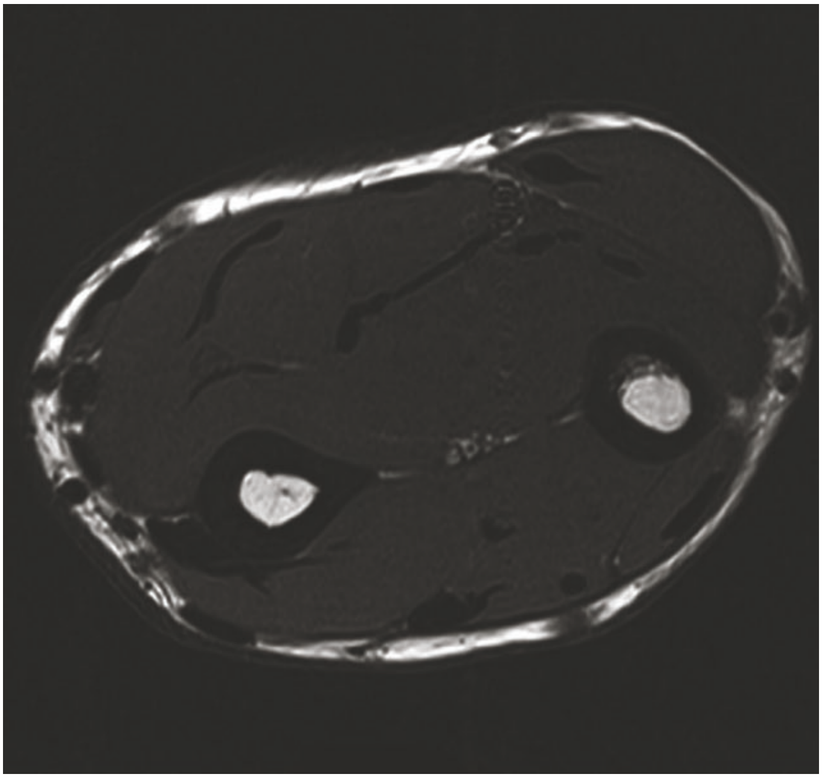
19- Basilic vein

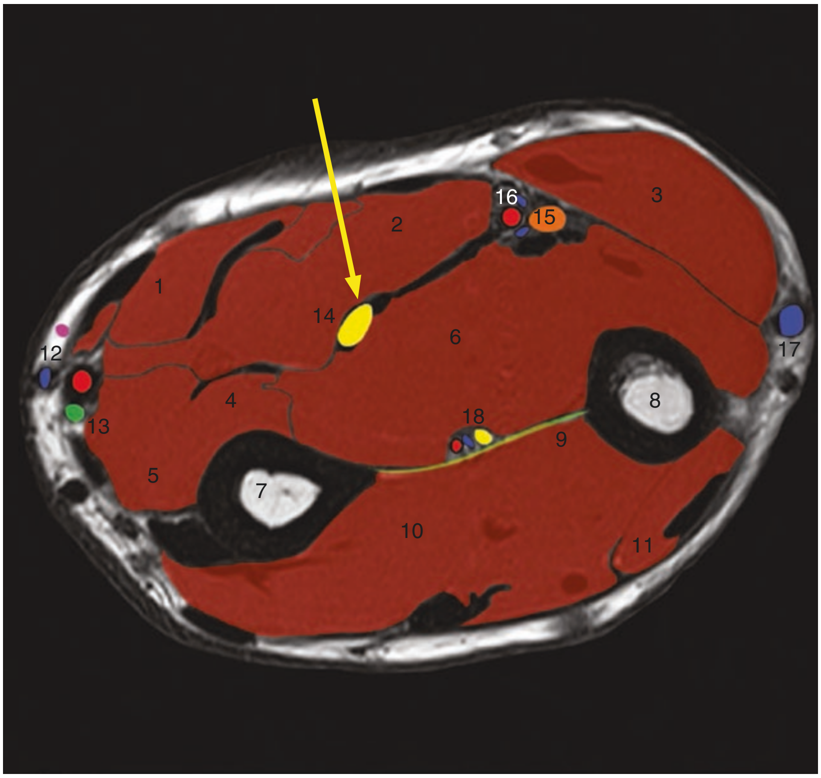
20- Radial nerve

21- Ulnar nerve

Figure M17. MRI scans in the elbow through the median nerve.

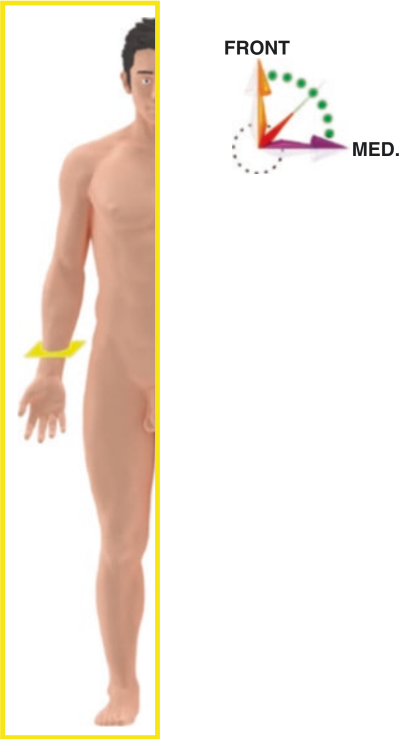


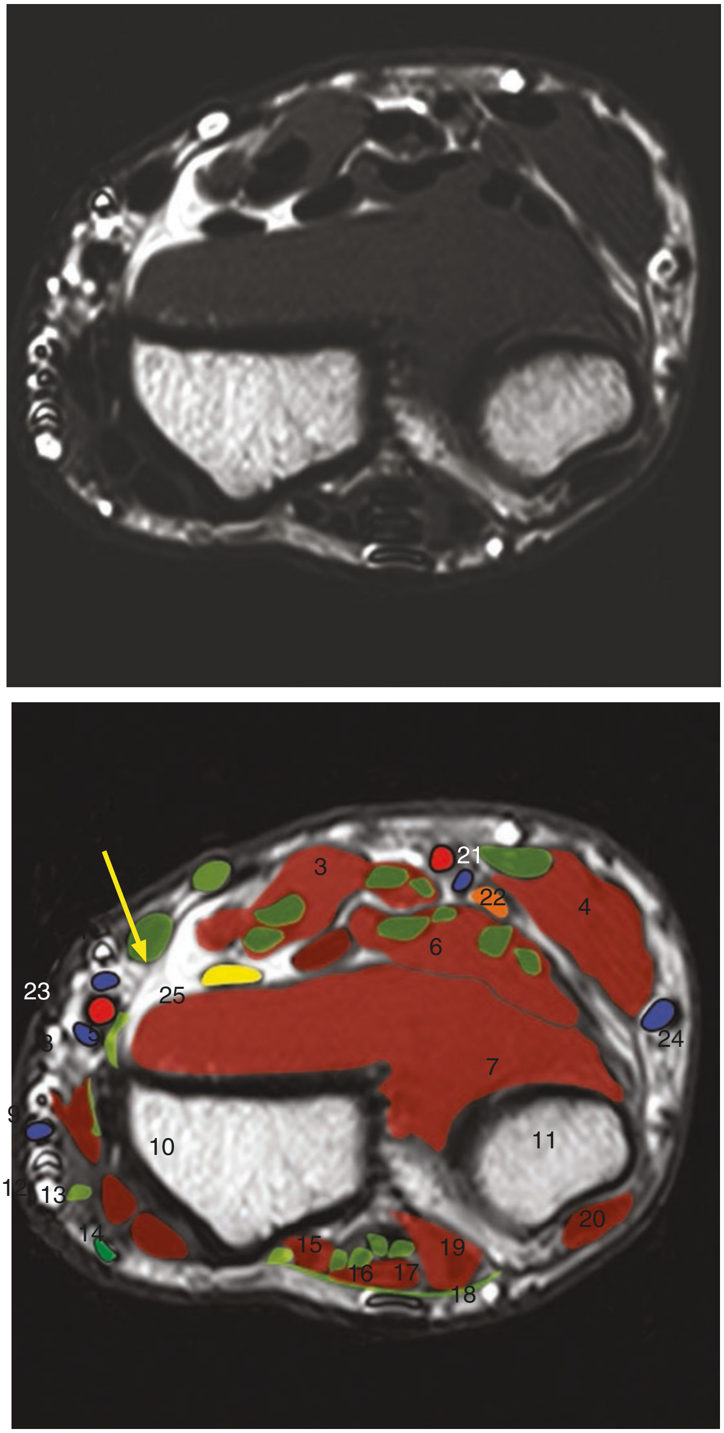




1- Flexor carpi radialis muscle
2- Flexor digitorum superficialis muscle
3- Flexor carpi ulnaris muscle
4- Flexor pollicis longus muscle
5- Extensor carpi radialis brevis muscle
6- Flexor digitorum profundus muscle
7- Radius
8- Ulna
9- Interosseous membrane of the forearm
10- Posterior compartment of the extensor digitorum muscles
11- Extensor carpi muscle
12- Radial artery and vein
13- Radial nerve
14- Median nerve
15- Ulnar nerve
16- Ulnar artery and vein
17- Basilic vein
18- Anterior interosseous artery, vein and nerve

Figure M18. MRI scans in the forearm through the median nerve.





1- Flexor carpi radialis muscle
2- Palmaris longus muscle
3- Flexor digitorum superficialis muscle
4- Flexor carpi ulnaris muscle
5- Flexor pollicis longus muscle
6- Flexor digitorum profundus muscle
7- Pronator quadratus muscle
8- Brachioradialis muscle
9- Abductor pollicis longus muscle
10- Radius
11- Ulna
12- Extensor pollicis brevis muscle
13- Extensor carpi radialis longus muscle
14- Extensor carpi radialis brevis muscle
15- Extensor pollicis longus muscle
16- Extensor digitorum muscle
17- Extensor digiti minimi muscle
18- Extensor retinaculum
19- Extensor indicis muscle
20- Extensor carpi muscle
21- Ulnar artery and vein
22- Ulnar nerve
23- Radial artery and vein
24- Basilic vein
25- Median nerve
26- Cephalic vein

Figure M19. MRI scans in the wrist through median nerve.

Pathology

We decided to insist on two characteristic syndromes of the median nerve (Figure M16):

- Carpal tunnel syndrome, important because of its frequency
- Anterior interosseous nerve syndrome (refer to the next section)

Anterior Interosseous Nerve Syndrome

As a reminder, the median nerve gives rise to the anterior interosseous nerve between the two heads of the pronator teres muscle. This motor branch innervates the flexor pollicis longus and brevis, the lateral part of the flexor digitorum profundus and the pronator quadratus in an autonomous way.

Its compression occurs under the arch of the flexor digitorum superficialis muscle. It is responsible for anterior interosseous nerve syndrome, also called Kiloh-Nevin syndrome. This rare syndrome only represents 1% of cases of entrapment neuropathy in the upper limb.

Aetiology

- Compression: This is the main injury mechanism of the anterior interosseous nerve. The injury is situated slightly ahead of the point where the nerve emerges, between 5 and 8 cm below the medial epicondyle of the humerus, under the arch of the flexor digitorum superficialis. This syndrome can occur by a prolonged local compression—sleep, restraint with a plaster cast, excessive physical exercise, repetitive lifting of heavy loads, etc.

Clinical Significance

- Sensitive signs: Pain in the upper third of the forearm is frequent, often by exacerbations lasting several hours, deep, but there is no objective trouble of sensitivity, which is what differentiates it from the other types of median nerve injuries. Pain is of mechanical type in 85% of cases.
- Motor signs: This syndrome includes a decrease in strength of flexion of the second phalanx of the thumb, index and middle fingers by injury of the flexor digitorum profundus and flexor pollicis longus muscles. The pinch test proves this since the patient uses the phalange's pulp instead of the extremity of the thumb and index—the pinch forms a triangle-like shape. The patient cannot make an O shape because of a deficit of the distal phalanges flexion (Figure M20). The deficit of pronation is more complex to show. A partial injury can only affect the flexor digitorum profundus.

Some ulnar fibres can be satellites of the interosseous nerve; in this case, the syndrome is accompanied by an injury of the intrinsic muscles in the hand.

Explorations

- Elbow radiography (bilateral and comparative) in order to search for a bone intumescence, especially at the level of the medial epicondyle.
- An electroneuromyography documents the nerve injury and gives the ability to set aside a differential diagnosis.

Treatment

The first treatment is the immobilization of the elbow. A surgical treatment is only required for a documented evolving compression, after 4 months of unsuccessful although well-run medical treatment.

Functional results are generally satisfying.

Carpal Tunnel Syndrome

The carpal tunnel syndrome is a compression of the median nerve in the wrist under the flexor retinaculum in the carpal tunnel. This syndrome can happen after repeated solicitations, generally in a professional context. General potential causes must not be ignored:

- Pregnancy
- Endocrinological causes: diabetes, hypothyroidism, acromegaly, hypercorticism
- Overload diseases: amyloidosis

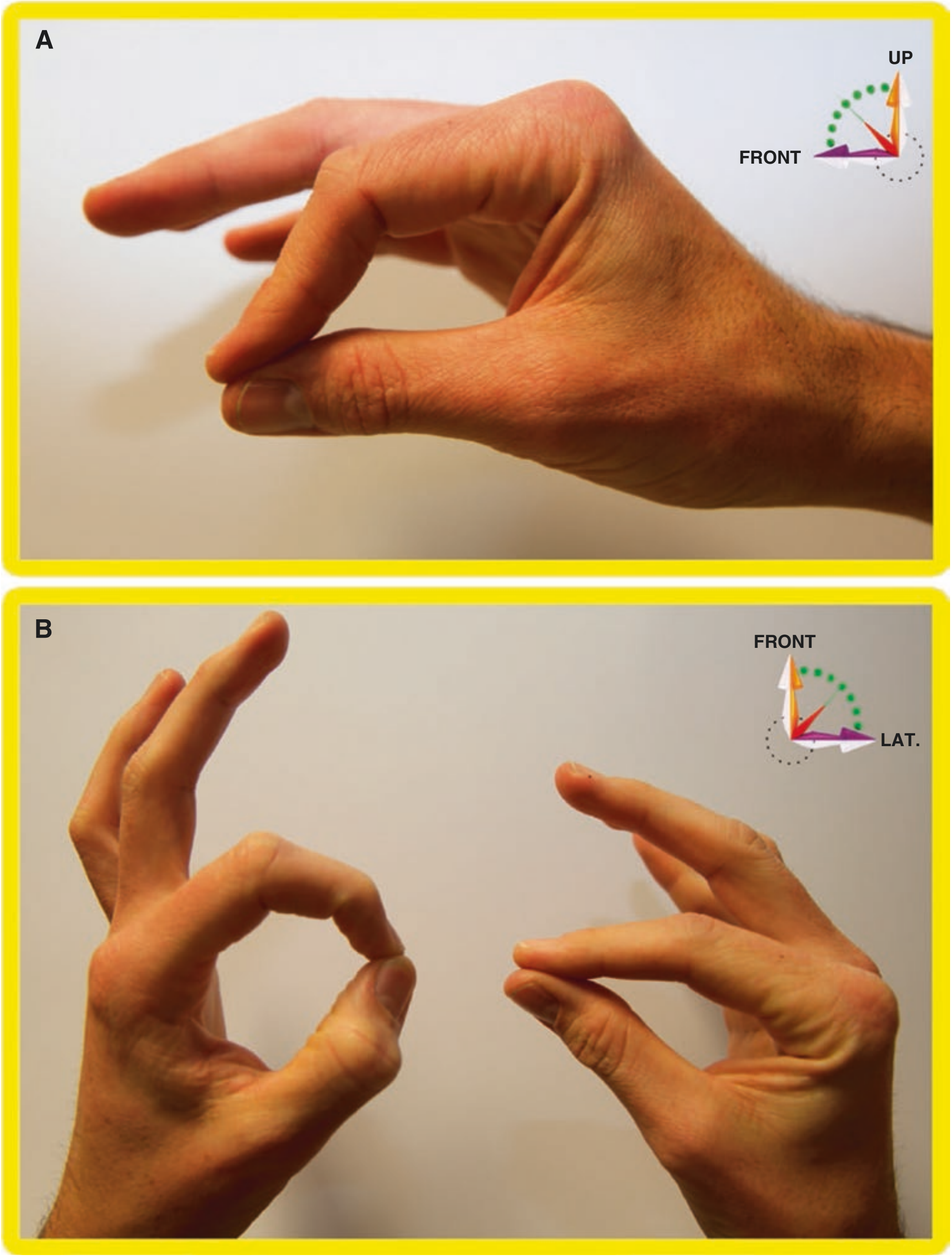


Figure M20. Paralysis of the left anterior interosseous nerve. Clinical significance: injury of the extensor indicis profundus and flexor pollicis longus muscles in the hand. The patient cannot make an O shape using the right thumb and index since pinch-type grips became impossible (injury of the flexor muscles).

The Median Nerve

Clinical Signs

Initially, the patient complains of paraesthesia, especially at night-time, in the sensitive territory of the median nerve.

When the injury is more evolved, a disuse atrophy of the thenar muscles can develop. In this case, a surgical decompression treatment is recommended.

It is important to note that an epicondylitis can be associated in 20% of cases.

The two classical clinical tests include:
- Tinel's sign, which reproduces the distal paraesthesia when hitting the retinaculum
- Phalen's sign, during a forced and extensive flexion of the hand on the forearm

Another test exists, which reproduces paraesthesia by inflating an armband on the forearm. This test is less often described.

As a final remark, note that an infiltration of the carpal tunnel can be interesting for a diagnosis.

Anatomical Atypias

When numerous, they cause atypias in the clinical syndrome.

Mainly represented are:
- An abnormal palmaris longus muscle, with the extremity of the fleshy body inside the carpal tunnel
- A higher division of the nerve with persistency of a median artery
- An abnormal path of the motor thenar branch that can start on the ulnar side and go through the retinaculum or its dorsal emergence
- An anastomosis between the median and ulnar nerves

Clinical Atypias

- The sensation of pain can extend to the forearm, directly ascending, and can reach the arm and even the neck, resembling cervicobrachial neuralgia.
- Clinical examination signs may not appear at all.
- A precocious disuse atrophy of the thenar muscles can dominate the clinical picture.
- The signs can affect the ulnar area and even predominate in this area.
- Trophic disorders can be in the foreground, especially in the form of oedema or sweating disorders.
- A curved finger is associated in 20% of cases.
- A metacarpal arthritis can partially tamper with the pain signs, much like a tenosynovitis.

Pregnancy can make a carpal tunnel syndrome more likely to appear, but will often disappear a few days after childbirth. In most cases, infiltration is a good solution that allows waiting for these signs to cease during the postnatal period.

Differential Diagnosis

It is in particular the diversity in the locations of clinical signs that can bring us to discuss:
- A radiculalgia of whichever origin, a cervicobrachial neuralgia being proof of a radicular injury
- A congenital agenesis of the thenar muscles

The responsibility of a neighbouring pathology: cyclist's palsy, bowler's thumb, tenosynovitis—sometimes associated with a thoracic outlet syndrome—and other entrapment neuropathies, Guyon's canal syndrome and semilunar injury.

Attacks of gout and leprosy are also rarely evoked.

Treatment

Setting aside the interest towards diagnosis mentioned above, infiltration can have a therapeutic interest, either when the trigger injury seems to have a limited duration such as pregnancy or following a contralateral surgery in order to improve the patient's comfort in bilateral forms.

A surgical treatment is recommended in case of an electro-clinical concordance and failure of infiltration for very moderate forms; it remains the treatment of choice for more severe forms (Figure M21).

Post-operative complications may happen, mainly during the first 6 months: adherent scar, occasionally acute pain during grips that require strength, local oedema, pain felt when pushing on the base of the hand, etc. The most formidable post-operative complication is rare, fortunately. It is a peri-operative injury of the motor thenar branch, especially in the case of an anatomical variation, which is responsible for a deficit in the flexion of the thumb–index pinch grip.

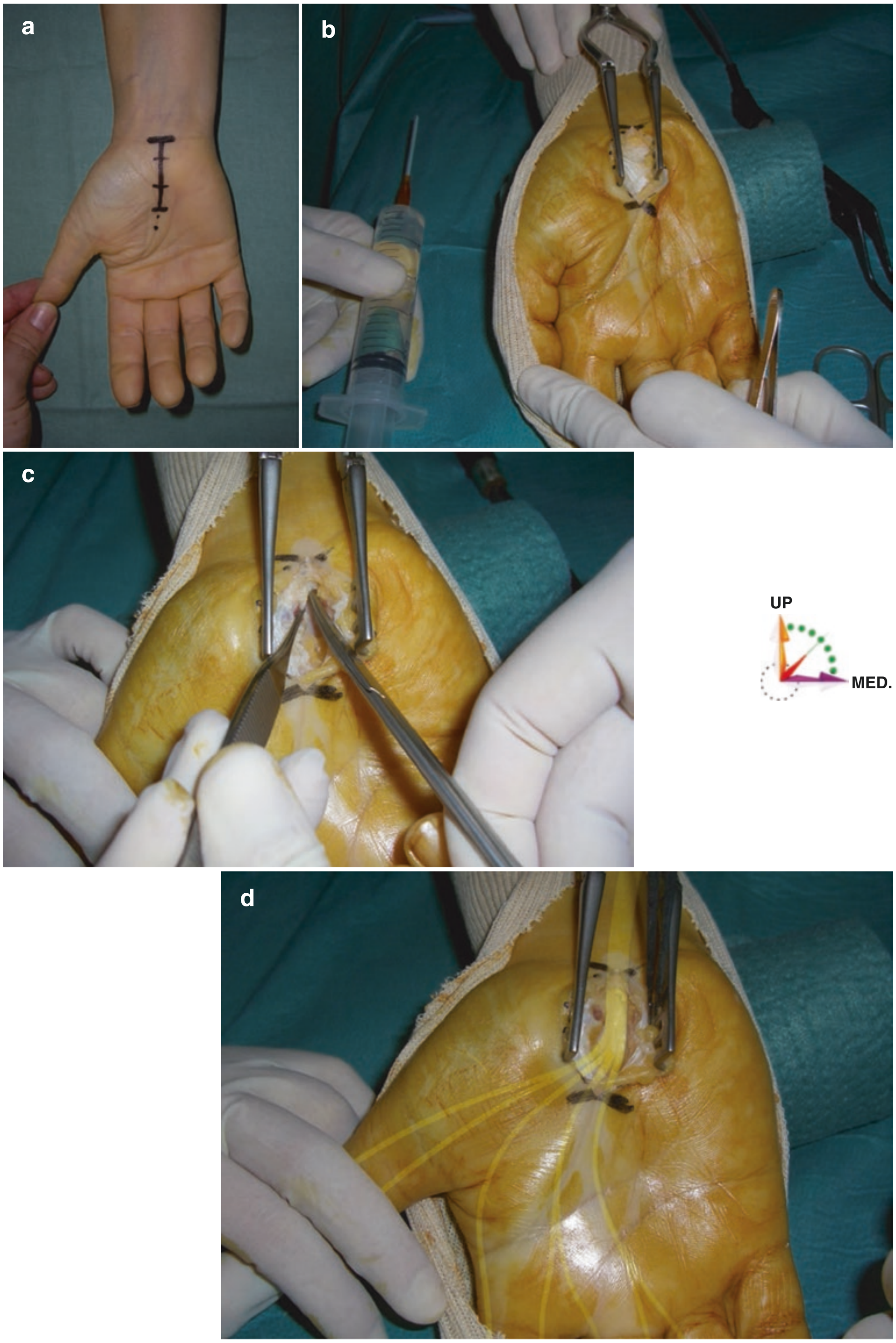


Figure M21. Carpal tunnel syndrome—open decompression surgery with incision of the flexor retinaculum allowing for the exposition and decompression of the median nerve (*).

Morphological Data: Sono Anatomy

Installation

The patient is in supine position, the arm in 90° abduction, the hand in supination.

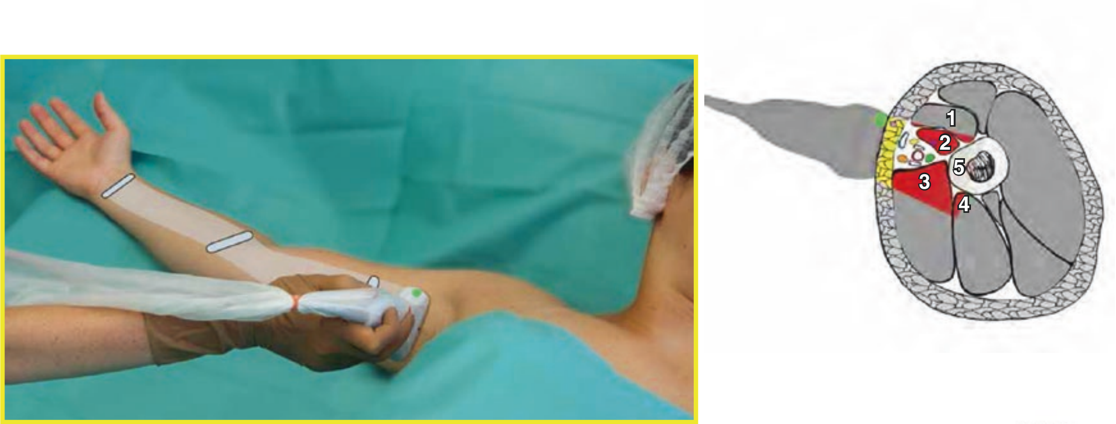
Equipment and Location

- Type of probe: surface, linear from 5 to 13 MHz
- Probe axis: parasagittal

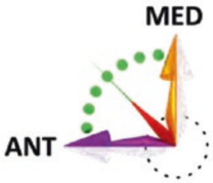
The skin marker is the anterior edge of the axillary cavity.

Ultrasound Procedure

The structures to be identified are vascular: artery and brachial vein, and muscular: the latissimus dorsi muscle. The aponeurosis of the tendon of the latissimus dorsi muscle is observed in the dorsal, i.e., in depth, while the biceps brachii muscle is observed in the front. Frequently accompanied by the deep brachial artery, the brachial artery is an easy anatomical landmark, with the median nerve and biceps brachii muscle in front of this structure.



1- Biceps brachii muscle
2- Coracobrachialis muscle
3- Latissimus dorsi muscle
4- Teres major muscle
5- Humerus
6- Brachialis artery
7- Brachialis veins
8- Cephalic vein
9- Basilic vein
10- Musculocutaneous nerve
11- Radial nerve
12- Median nerve



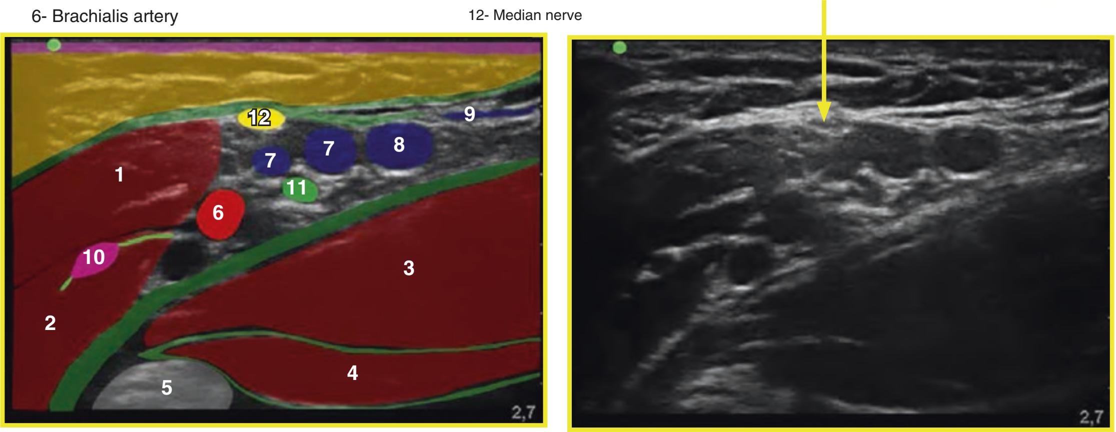
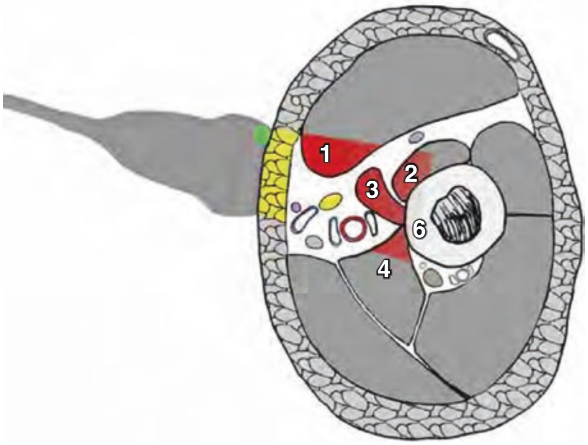
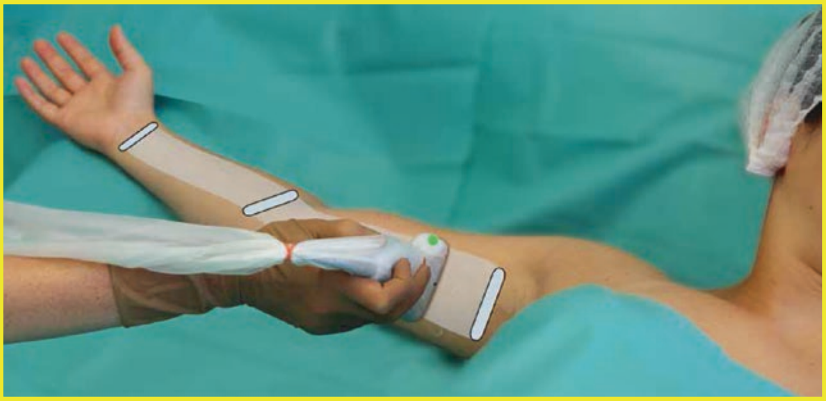


Figure M22. Ultrasound transversal views of the median nerve at the distal third of the axillary pit.

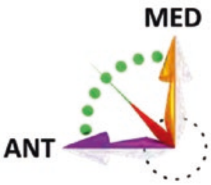
The median nerve descends into the humeral canal at the medial surface of the arm in contact with the artery, snakes around the axillary artery at its lateral edge, at its ventral surface and finally at the medial edge of the artery.



An ultrasound scan from proximal to distal is then performed. The probe is lowered along the arm to its middle third, so the position of the probe is medial to the arm. This region delimits the humeral canal. At this level, the landmarks are muscular, with the biceps brachii muscle in the anterior and triceps brachii muscle in the posterior, and vascular, with the brachial artery. The medial nerve remains in contact with the brachial artery throughout the crossing of the humeral canal. The medial nerve is in contact with the biceps brachii muscle, the brachial artery remaining medial.



1- Biceps brachii muscle
2- Brachialis muscle
3- Coracobrachialis muscle
4- Triceps brachii muscle
5- Medial intermuscular septum
6- Humerus
7- Brachialis artery
8- Brachialis vein
9- Median nerve



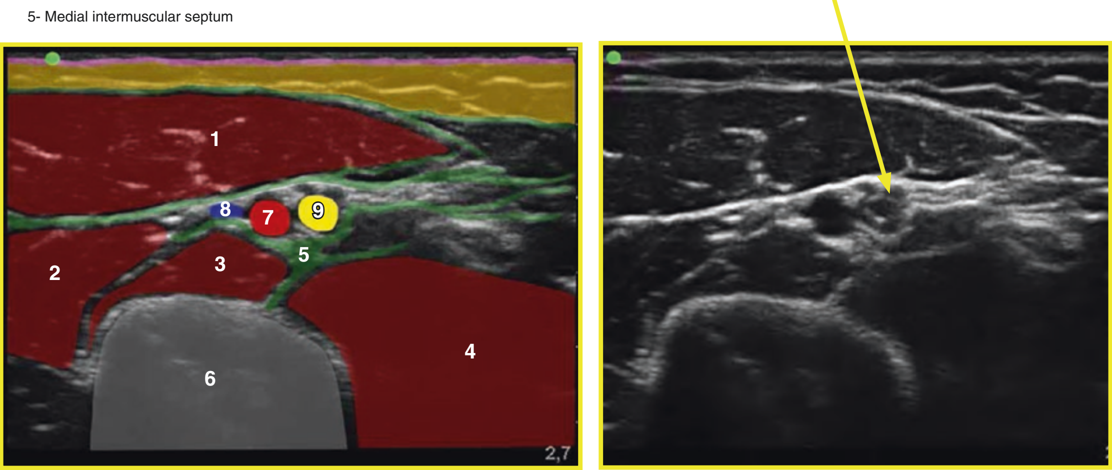
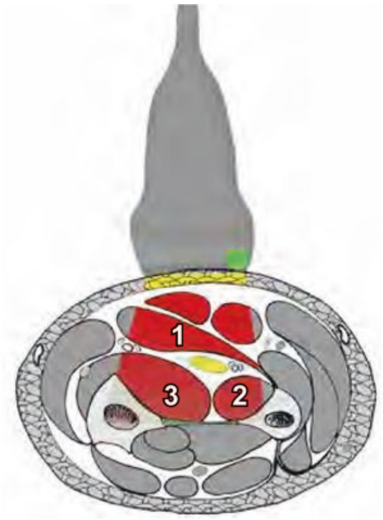
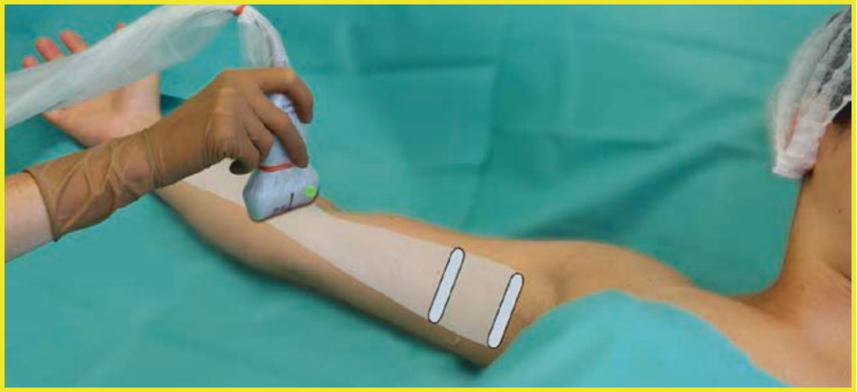


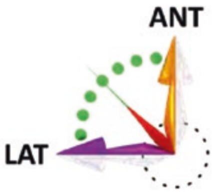
Figure M23. Ultrasound transversal views of the median nerve at the middle tier of the arm.

At the elbow, the nerve under the aponeurotic arch of the biceps brachii muscle is superficial and then dives deeper between the two heads of the pronator teres muscle in medial position. Then, it slides under the fibrous arch of the flexor digitorum superficialis muscle and descends between the flexor digitorum superficialis tendons of the second and third fingers.

In the middle third of the arm, the probe is positioned anteriorly in the axial plane, the median nerve is located between the flexor digitorum superficialis muscles at the top and flexor digitorum profundus muscles at the bottom. The interosseous membrane of the forearm can be found at this level.







1- Flexor digitorum superficialis muscle

2- Flexor pollicis longus muscle

3- Flexor digitorum profundus muscle

4- Interosseous membrane of the forearm

5- Radius

6- Ulna

7- Ulnar artery

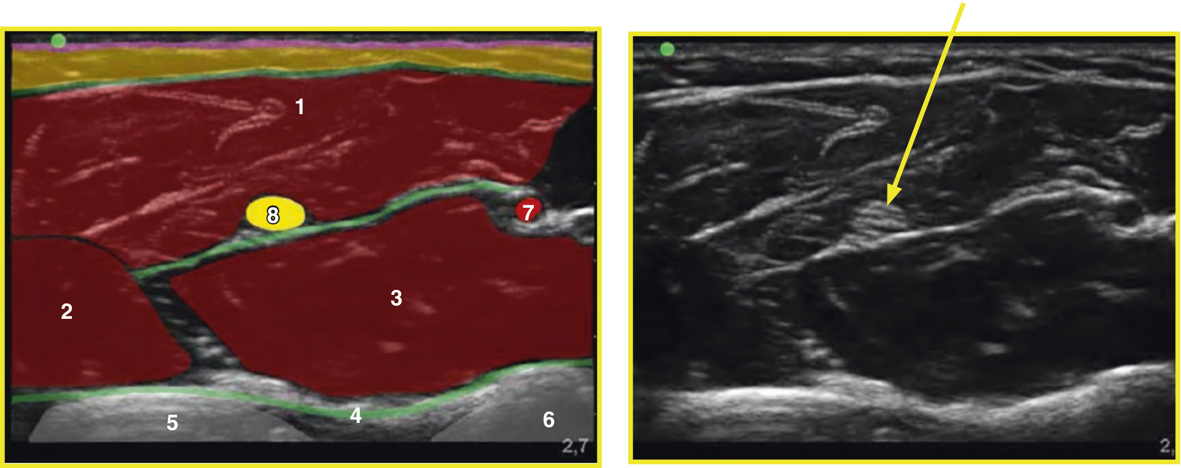
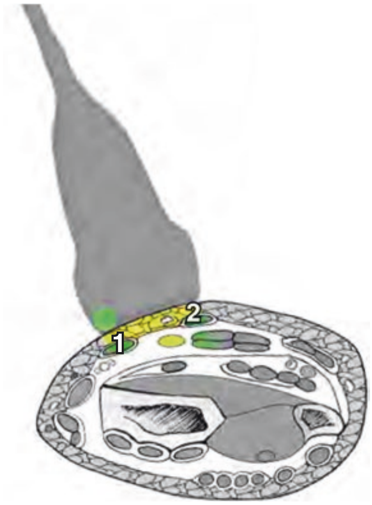
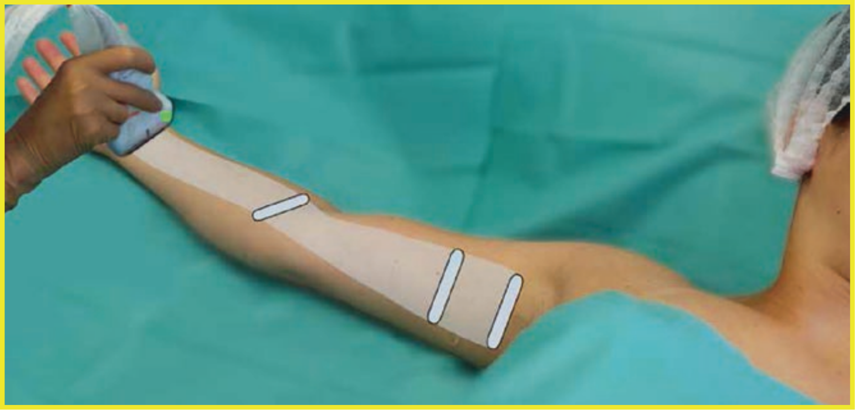


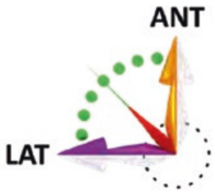
Figure M24. Ultrasound transversal views of the median nerve at the junction of the proximal third and middle tier of the forearm.

A few centimetres above the wrist, in a more superficial and lateral direction, inside the tendon of the flexor carpi radialis muscle, the median nerve engages in the carpal tunnel in front of the tendon of the flexor digitorum superficialis muscle. At this level, the motor and sensory branches can anastomose with the ulnar nerve.

In the carpal tunnel, the probe is located at the front face of the forearm in axial position. The median nerve is anterior, very superficial, occasionally covered by the tendon of the palmaris longus muscle. It is located between the tendons of the flexor carpi radialis muscle medially and the flexor digitorum profundus muscle laterally. We also note the presence of the radial artery laterally. At times, it is possible to visualize the median artery more laterally.







1- Tendon of the flexor carpi radialis muscle

2- Tendon of the palmaris longus muscle

3- Flexor retinaculum

4- Median nerve

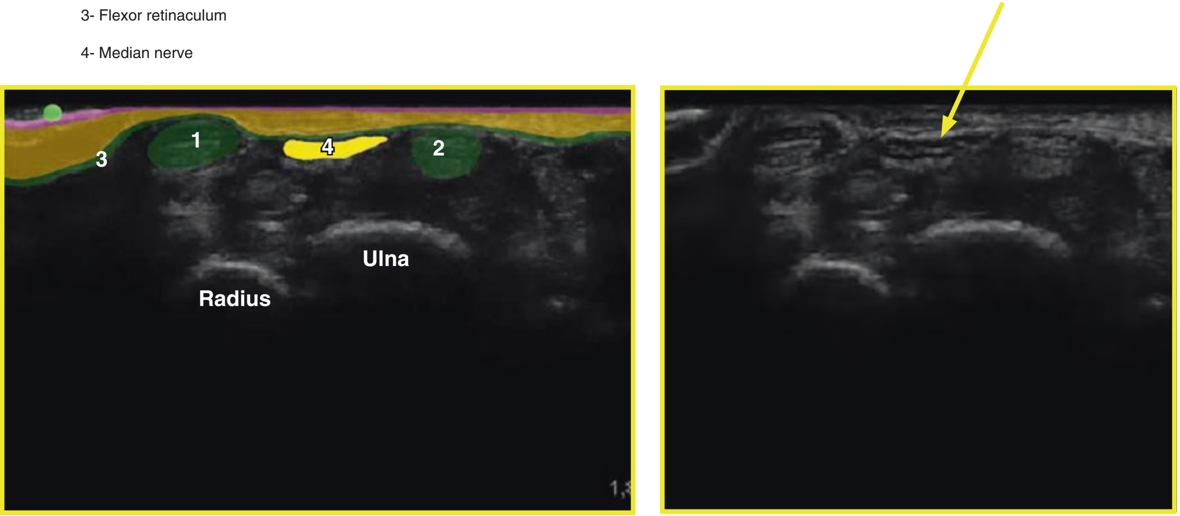


Figure M25. Ultrasound transversal views of the median nerve at radiopalmar crease (proximal part of the carpal tunnel).

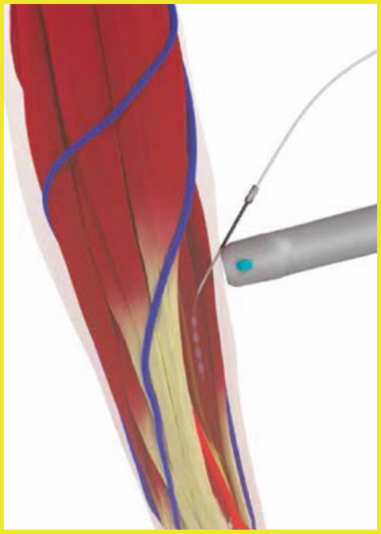
Interventional Procedure

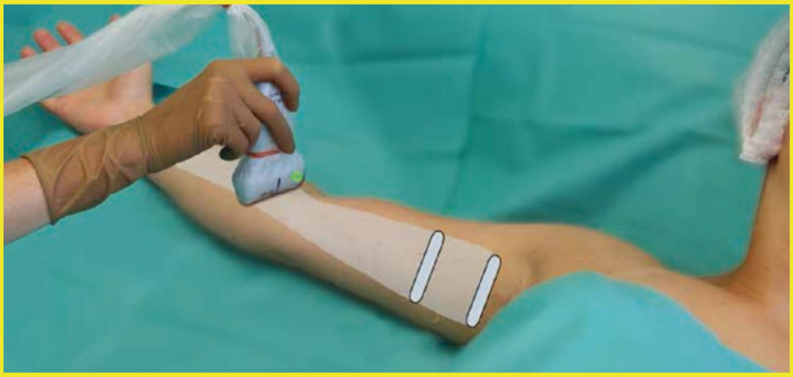
PNS

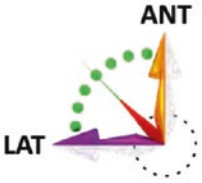
The ultrasound approach of the median nerve is preferred in the middle third of the forearm, the lead being inserted in an axial plane. First of all, it will be necessary to follow the nerve path to position the lead as perpendicularly to it as possible and to place the target in the centre of the screen.

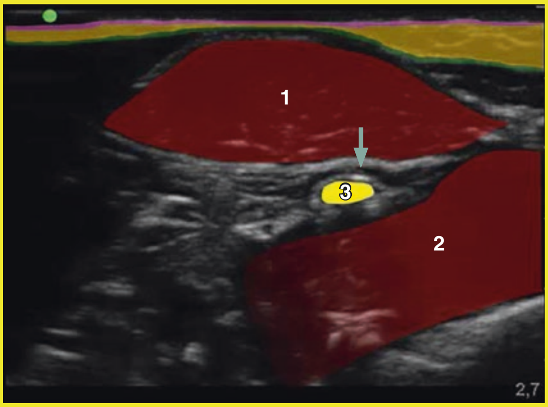
The stimulation electrode will be introduced percutaneously, with the needle oriented towards distality, in out-of-plane mode.

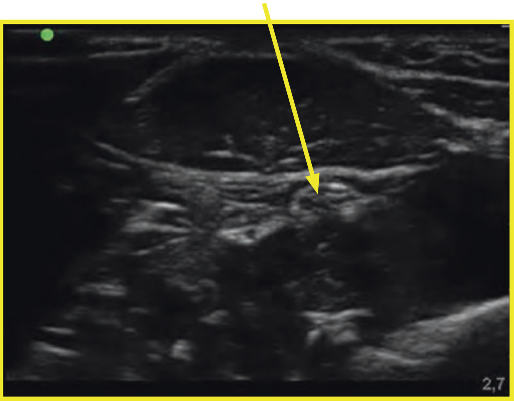
Hydrodissection is mandatory, by checking the correct positioning of at least two of the four plots (or eight for long electrodes) under ultrasound control, as close as possible to the nerve (Figures M26 and M27a). The definitive electrode will be placed between the flexor digitorum superficialis and flexor digitorum profundus muscles, while the generator can be implanted in the subclavicular region or the axillary cavity. For smaller stimulators, the operator can implant it directly on the arm.











1- Flexor digitorum superficialis muscle
2- Flexor digitorum profundus muscle
3- Median nerve
Lead contacts

Figure M26. Peripheral nerve stimulation of the median nerve at the junction of proximal third and middle tier of forearm, under ultrasound guidance.

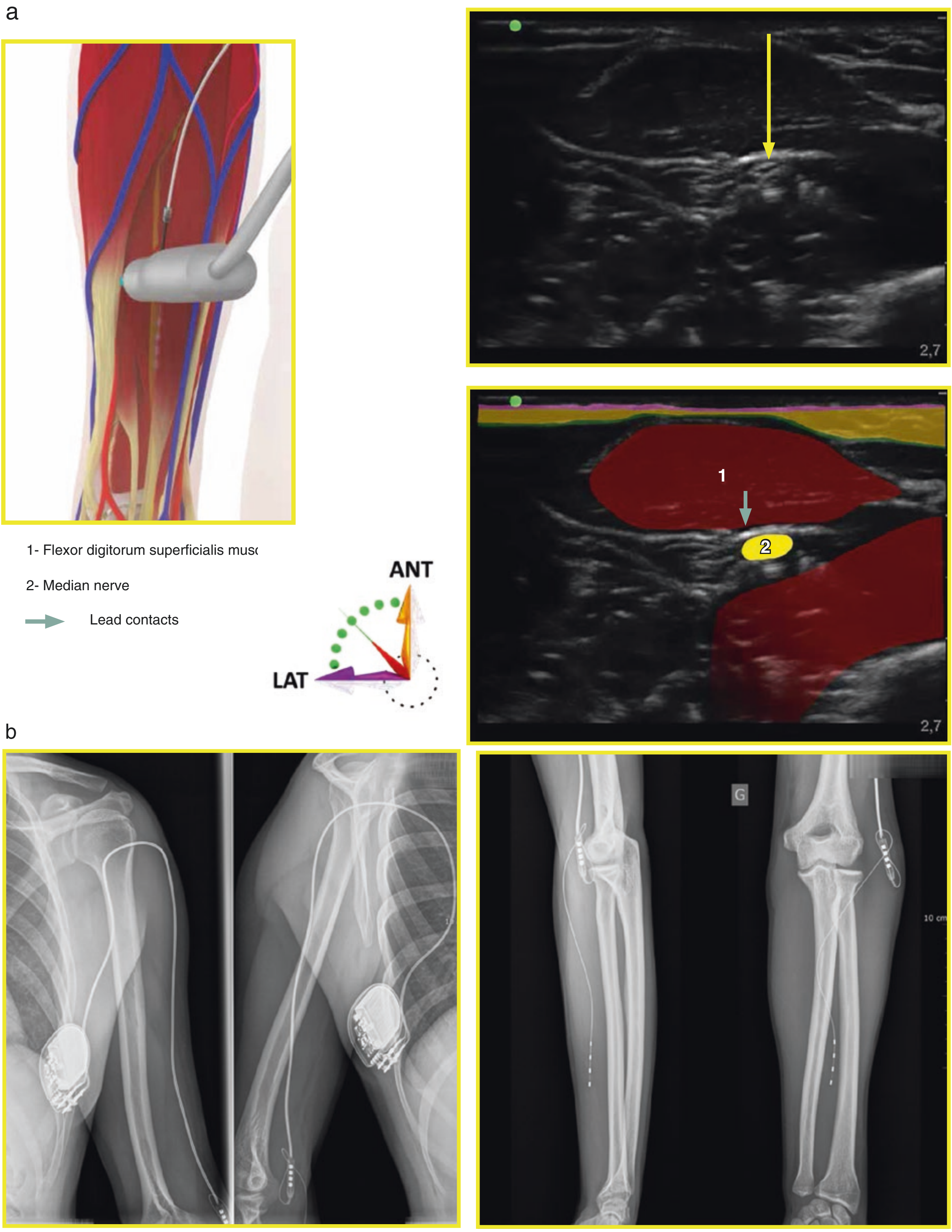

a
1- Flexor digitorum superficialis musc
2- Median nerve
Lead contacts
ANT
LAT
1
2
2,7
2,7
b
G
10 cm

Figure M27. Some illustrative views of median nerve neurostimulation. (**a**) Ultrasound guidance. (**b**) Post-operative X-ray showing the position of the lead at the middle third of the forearm.

Ultrasound Pathology

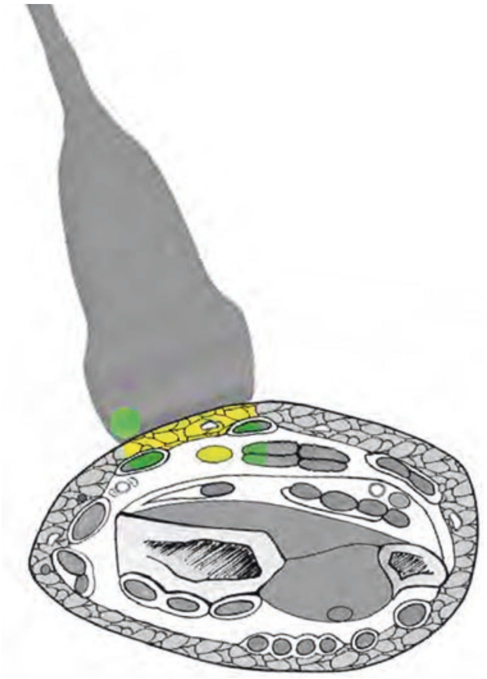
In carpal tunnel syndrome, ultrasound is a rapid, inexpensive and non-invasive diagnostic tool.

It allows the identification of a possible underlying cause (tenosynovitis, schwannoma, extrinsic compression).

In proven forms, ultrasound signs may correspond to an increase in volume, a change in nerve structure, neuronal hypervascularization, with the characteristic sign of a notch found at the level of the conflict.

In Figure M29a, we can see a pathological median nerve.

Figure M29b shows oedema of the median nerve upstream of the carpal tunnel, the nerve being enlarged and its usual fascicle structure replaced by a homogeneous hypoechoic aspect. In Figure M29c, the section of the nerve is increased, reflecting an increase in nerve volume upstream of stenosis.



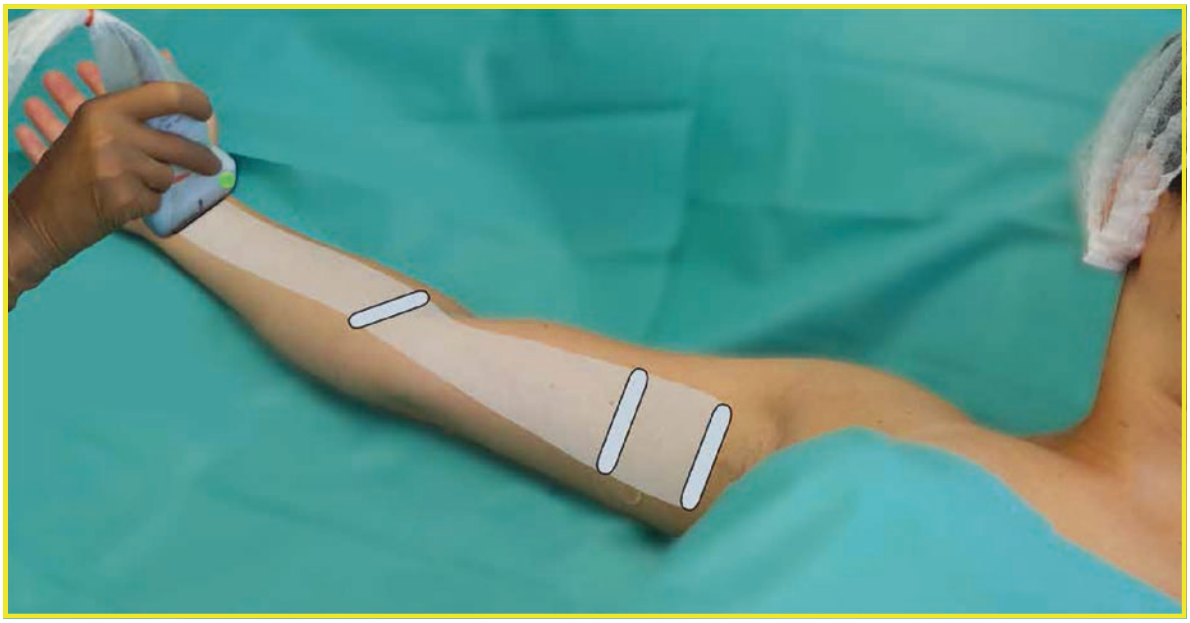


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Figure M28. Ultrasound guidance of the median nerve at the carpal tunnel entry.

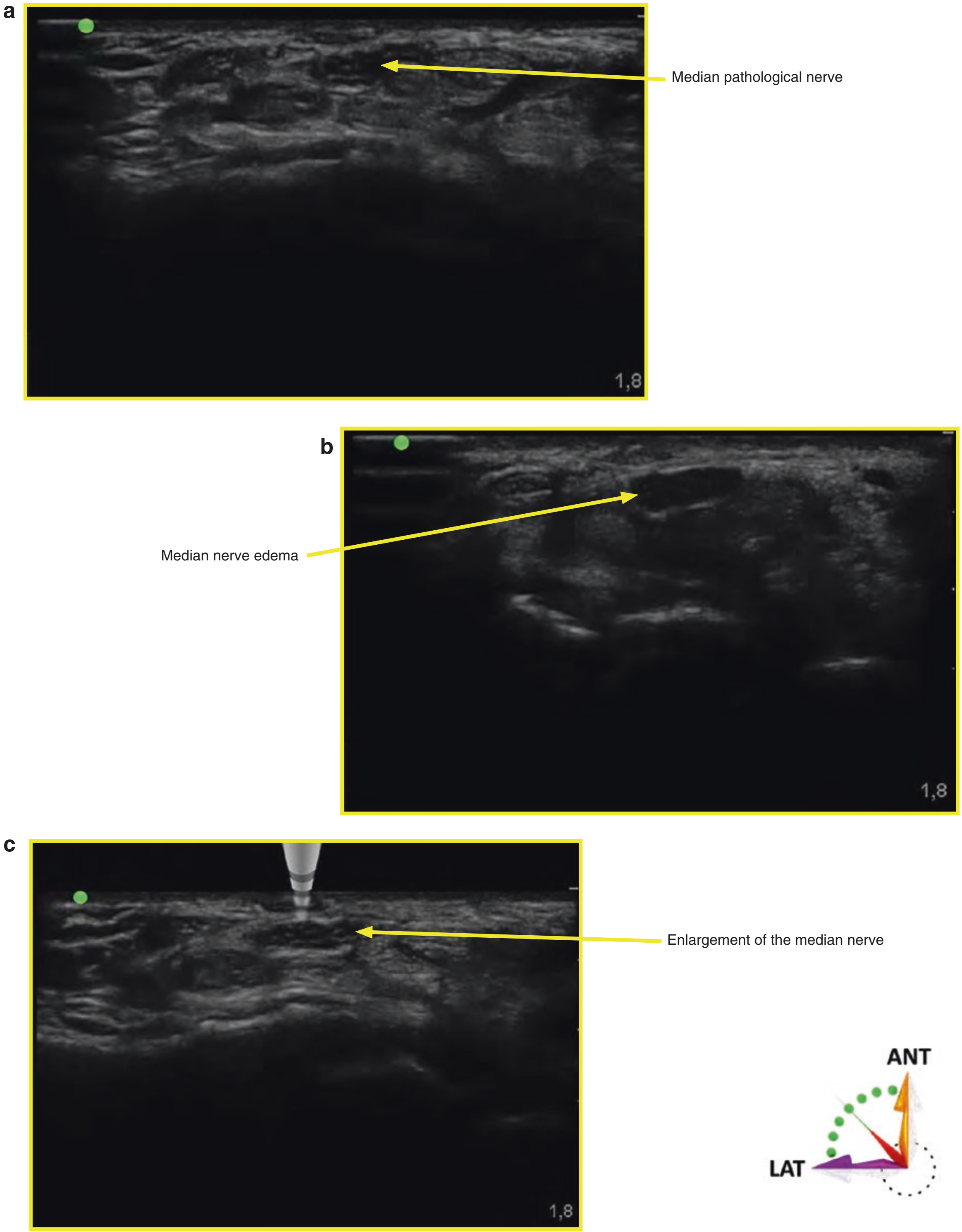

a
Median pathological nerve
1,8
b
Median nerve edema
1,8
c
Enlargement of the median nerve
1,8
ANT
LAT

Figure M29. Consecutive transversal ultrasound views of a median nerve compressed at the carpal tunnel level. (**a**) Ultrasound guidance of the median nerve. (**b**) Intra-nervous oedema responsible for "swelling" of the nerve. (**c**) Spread median nerve, reflecting an axonal flow decrease just upstream to the compression. Optimal position of the needle to infiltrate the nerve (out-of-plane technique).

Surgical Procedure

Surgical Approaches

Skin Incision

This incision requires positioning the arm in abduction and extends from the posteromedial edge of the biceps brachii muscle to the top of the armpit, and then along the anteromedial region of the arm to the medial epicondyle.

At the elbow, as is the case with the radial nerve, the skin incision corresponds to an S, but in medial axial symmetry, starting at the medial edge of the arm a few centimetres above the fold of the elbow and ending on the anterolateral side of the forearm after crossing the fold of the elbow (Figure M31).

At the forearm, the previous incision is extended vertically in its axis, but "waves" are made by a curvilinear trace, towards the wrist, to isolate the median nerve and its anterior interosseous branch on depth (Figure M33).

On the Arm

Nervous Exposure

Once the fascia has been severed, the posterior edge of the coracobrachialis muscle and then the posterior edge of the biceps brachii muscle can be removed to locate the median nerve just behind, first behind the coracobrachialis muscle and then in the groove between the biceps brachii and brachialis muscles. The basilic vein and the medial cutaneous nerve of forearm are located at the lower part of the incision (Figure M31). The median nerve has no branches at this level, which makes it easier to identify and dissect. It is located entirely in front of the internal intermuscular septum, near the ulnar nerve up to the middle part of the arm, where it is pierced by the ulnar nerve, and into the posterior brachial chamber (Figure M32).

At the Elbow

Nervous Exposure

The basilic vein sometimes hinders access to the deep plane and requires ligation. The aponeurosis of the biceps brachii muscle and its medial expansion are incised.

At the upper part of the incision, the muscle biceps brachii along which the humeral artery travels is identified, bordered inwards by the median nerve, before its division into radial and ulnar arteries. The median nerve passes at this level between the two leaders of the pronator teres muscle by innervating it as it passes. By receding the epicondylial chief of this muscle on the ulnar side, there is a cleavage plane to the arch of the flexor digitorum superficialis muscle into which the median nerve engages.

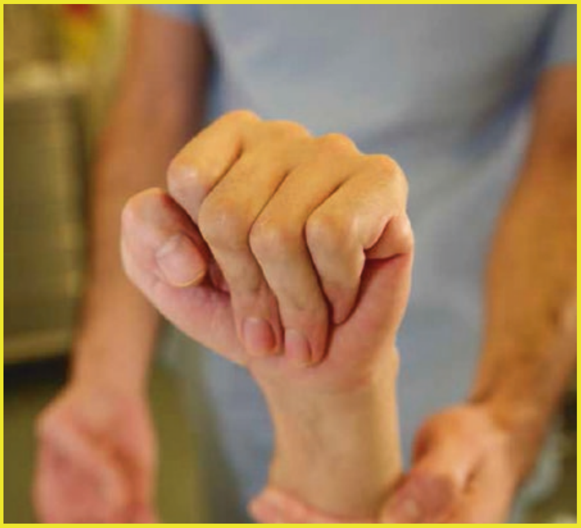


Figure M30. Spastic hand after a stroke. Indication of a median nerve neurotomy after repeated injections of botulinum toxin into the flexor muscles of the fingers.

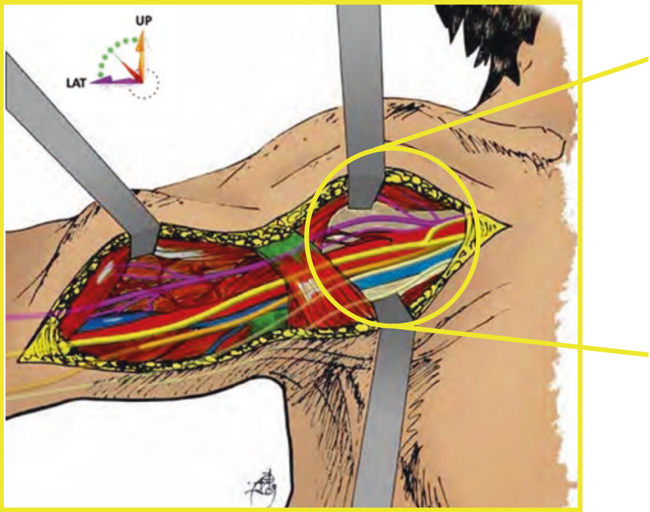
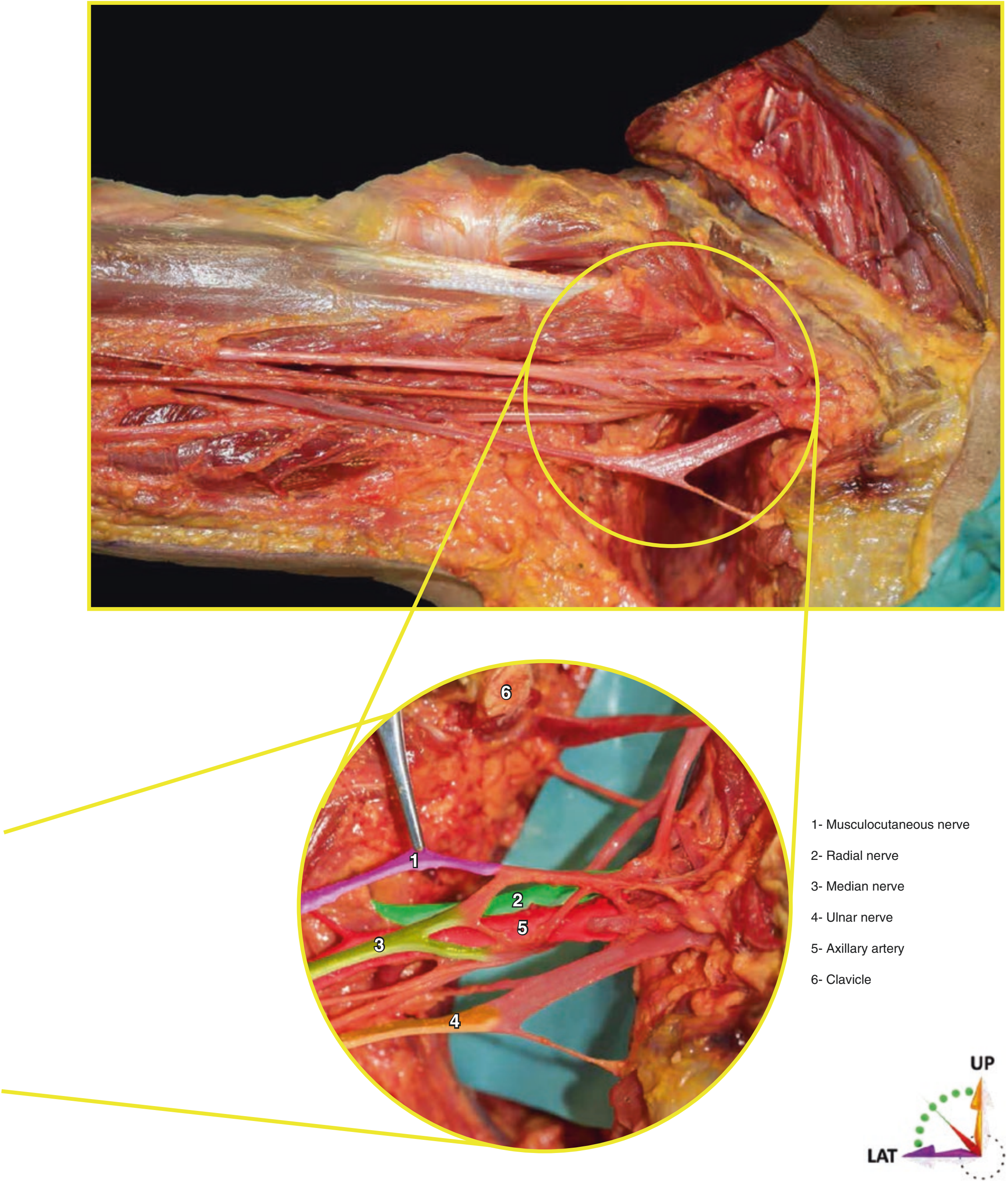


Figure M31. Surgical approach of the median nerve.



1- Musculocutaneous nerve
2- Radial nerve
3- Median nerve
4- Ulnar nerve
5- Axillary artery
6- Clavicle

Figure M32. Vasculo-nervous relationships of the median nerve and its bundles at the axillary pit level.

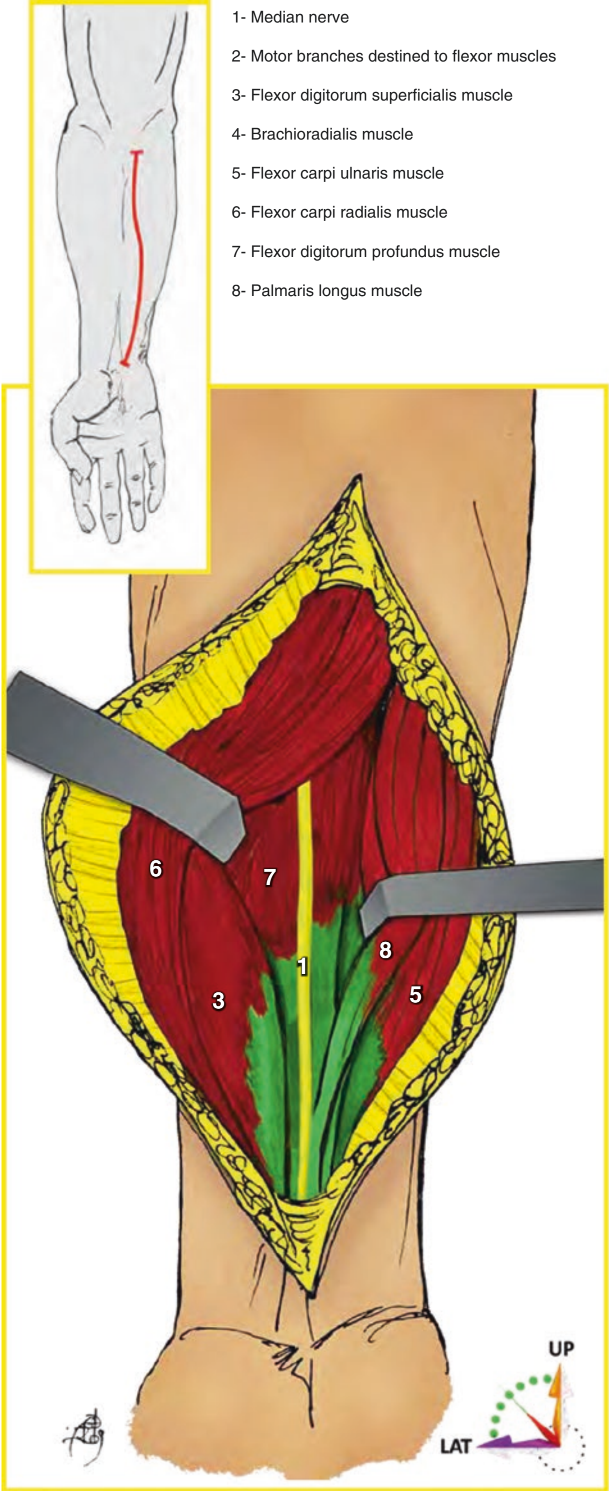
At the Forearm

Nervous Exposure

A section of the flexor digitorum superficialis muscle allows easier exposure of the nerve, in return for a certain degree of muscle decay.

To continue the dissection, it is necessary to refine the flexor carpi radialis muscle inside and outside the brachioradialis muscle, allowing the flexor digitorum superficialis muscle and its arch to be clearly exposed, on the deep face of which the nerve travels in a relatively adherent fibrous tissue. The anterior interosseous branch detaches from the nerve when it passes to the deep face of the superficial chief of the pronator teres muscle, at the posterior surface of the median nerve. It descends along the interosseous membrane between the flexor digitorum profundus and the flexor pollicis longus muscle, unchecking specific motor innervation branches (Figures M33 and M35). It also supports the innervation of the lateral half of the flexor digitorum profundus muscle. Accompanied by the anterior interosseous artery, it travels to the carpal tunnel by sending deep twigs to the prostate gland and wrist joint. This route has the advantage of allowing common exposure of the median nerve and its anterior interosseous branch.

If it is only necessary to expose the median nerve to the forearm, a more internal curved incision is preferred by passing between the flexor carpi radialis and flexor digitorum superficialis tandem outside and the palmaris longus/flexor carpi ulnaris tandem inside. It is not possible to go up beyond the fibrous arch of the flexor digitorum superficialis muscle without monobloc disinserting the flexor from its radial insertion, which requires an approach of the nerve through the previously described, more lateral incision.



1- Median nerve
2- Motor branches destined to flexor muscles
3- Flexor digitorum superficialis muscle
4- Brachioradialis muscle
5- Flexor carpi ulnaris muscle
6- Flexor carpi radialis muscle
7- Flexor digitorum profundus muscle
8- Palmaris longus muscle

Figure M33. Surgical approach of the median nerve at the forearm level.

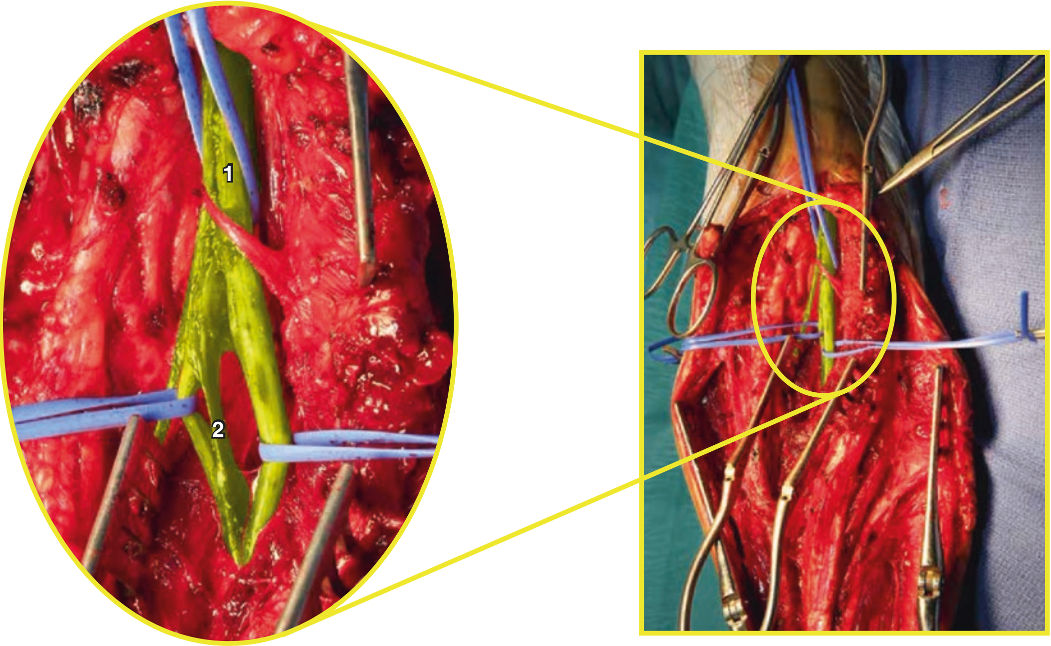


Figure M34. Surgical approach of the median nerve at the forearm proximal third.

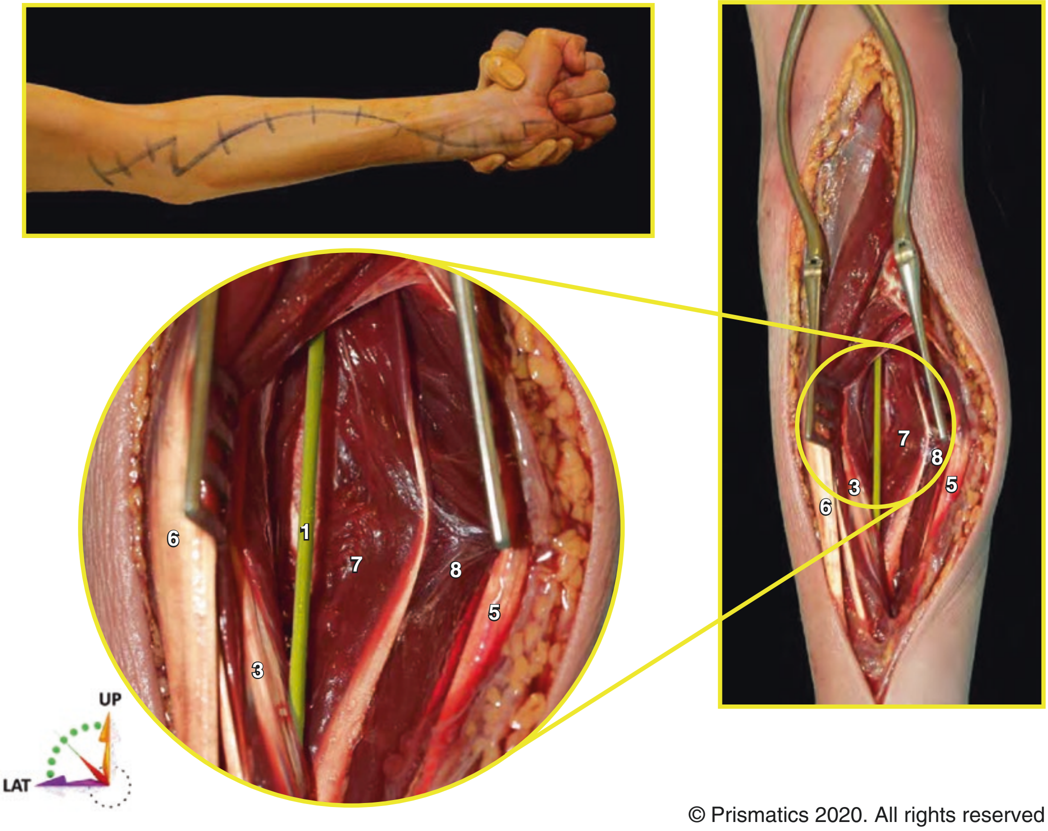

7
8
3
5
6
6
1
7
8
5
3
UP
LAT

Figure M35. Surgical approach of the median nerve at the forearm middle tier.

By Hand

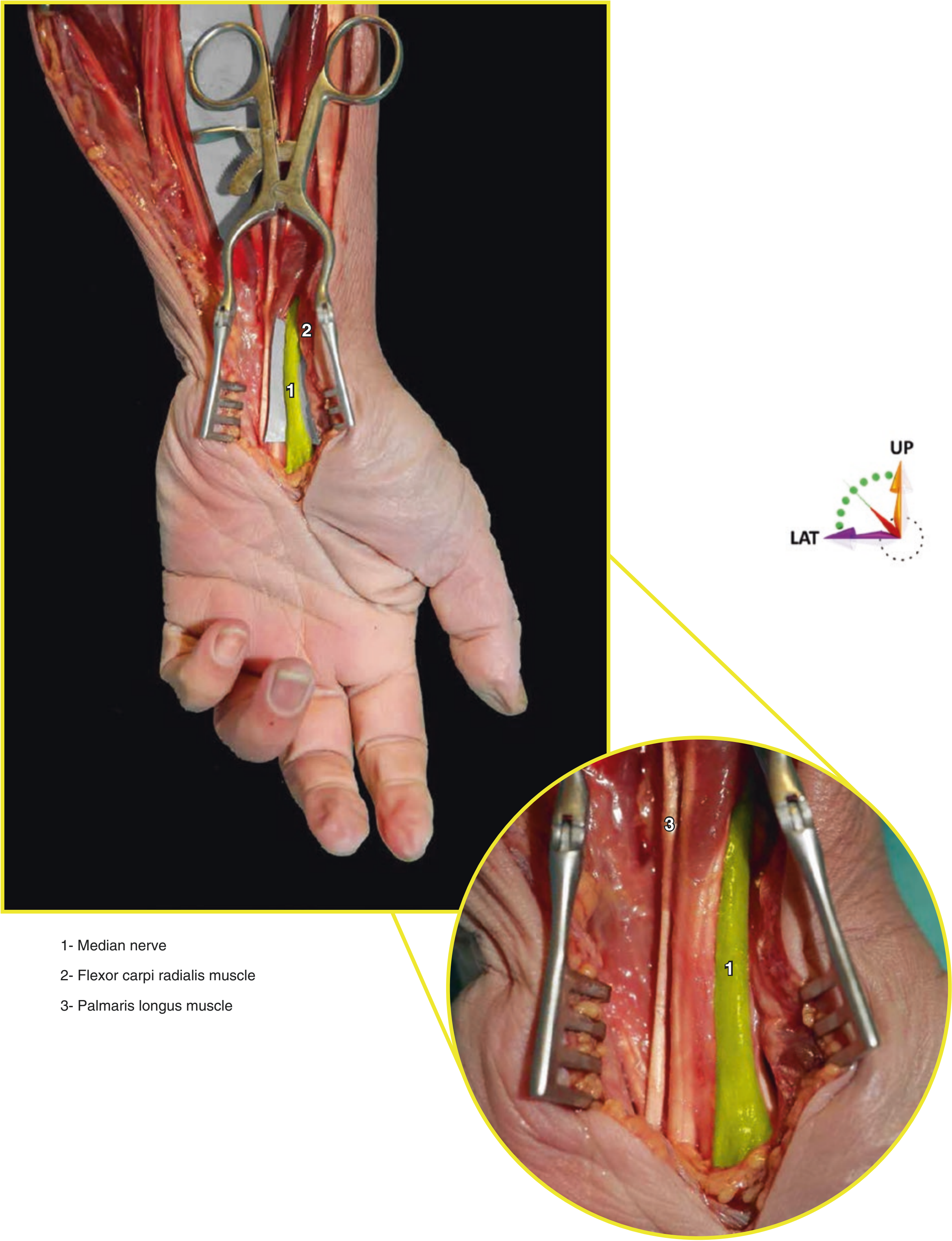
Nervous Exposure

This surgery essentially concerns release of the median nerve in the carpal tunnel or removal of an intra- or perinervous tumour lesion, or a neurotomy of the thenarian branch, or else its repair.

While most authors advocate a curvilinear incision along the fold of the thenar eminence, others document neuroma if one decides not to spare the superficial cutaneous branches of the median and ulnar nerves in the palm, and they prefer a much more lateral incision, straddling the carpal tunnel and Guyon's box. It begins at the distal flexion fold of the wrist and curves towards the thumb for some and towards the base of the ring finger for others (it would then ideally travel between the cutaneous branches of the median and ulnar nerves). At the proximal part of the surgical field, the tendon of the palmaris longus muscle is easily recognized. It is necessary at this level to descend to its radial edge to expose the median nerve. With respect to the retinaculum of the carpal flexors, the palmaris longus muscle merges with the palmar aponeurosis (Figure M36). The flexor retinaculum of the hand is then incised, taking care not to leave any residual fibres responsible for persistent compression. It is necessary to check that the release is optimal proximally, if necessary by cutting the distal fascia of the forearm. The palmaris longus muscle, flexor retinaculum of the hand and palmar aponeurosis can then be retracted to expose the median nerve, which is plated on the flexor tendons that pass through the carpal tunnel. We can identify its motor branch, the site of anatomical variations that must be known. Distally from the flexor retinaculum of the hand, the median nerve is divided into digital and thenarian branches (to innervate the abductor pollicis brevis, opponens pollicis and superficial bundle of the flexor pollicis brevis muscles). Two sensitive branches will share the cutaneous innervation of the thumb.

Technical Pitfalls

- Retractile scars due to excessively straight incisions, especially on the forearm
- Vascular lesions of the arteries of the arm and forearm



1- Median nerve

2- Flexor carpi radialis muscle

3- Palmaris longus muscle

Figure M36. Surgical approach of the median nerve at the hand level.

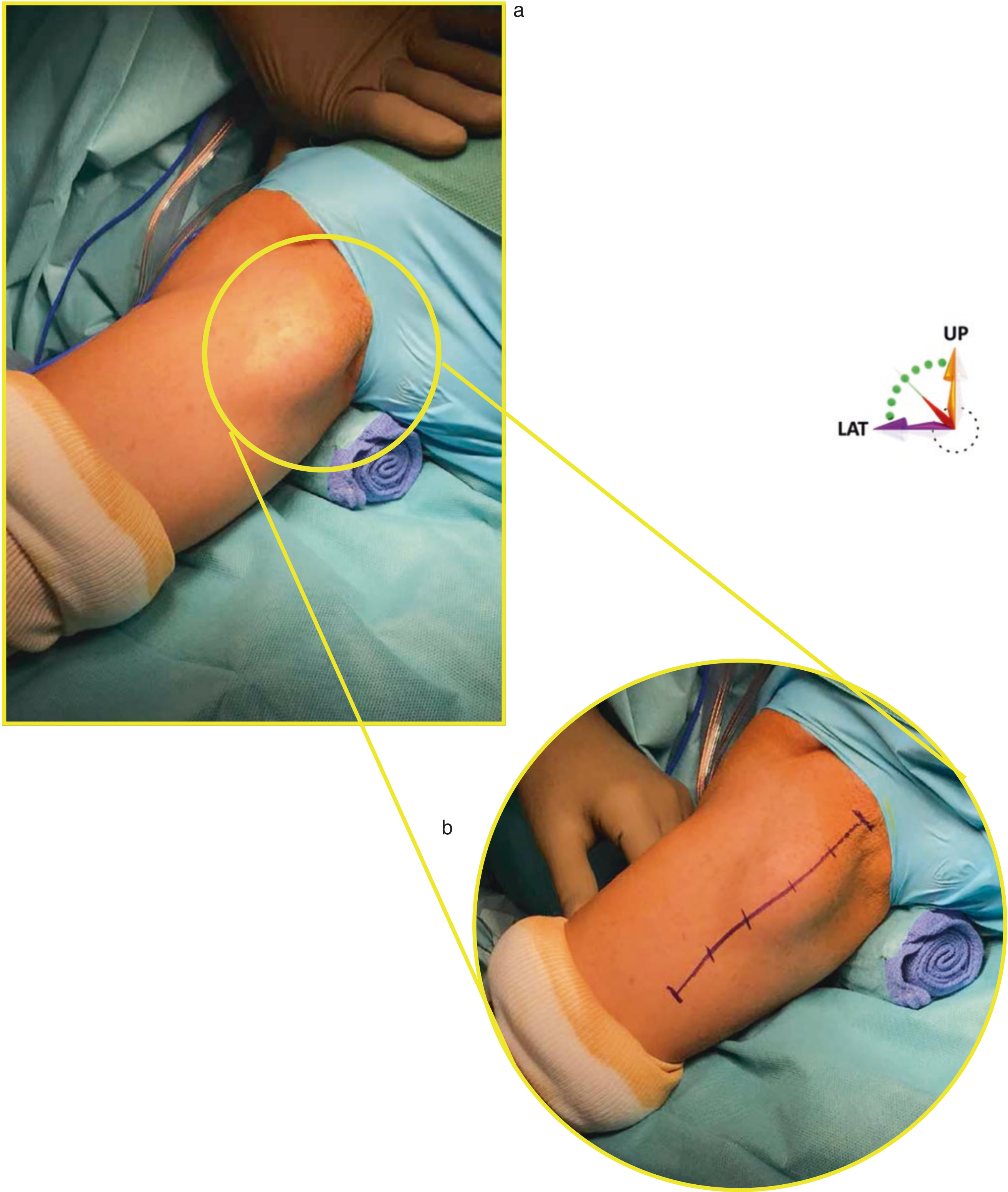


Figure M37. Median nerve neuroma in the arm. (**a**) Visualization of a voluminous mass in the arm. (**b**) Surgical approach.

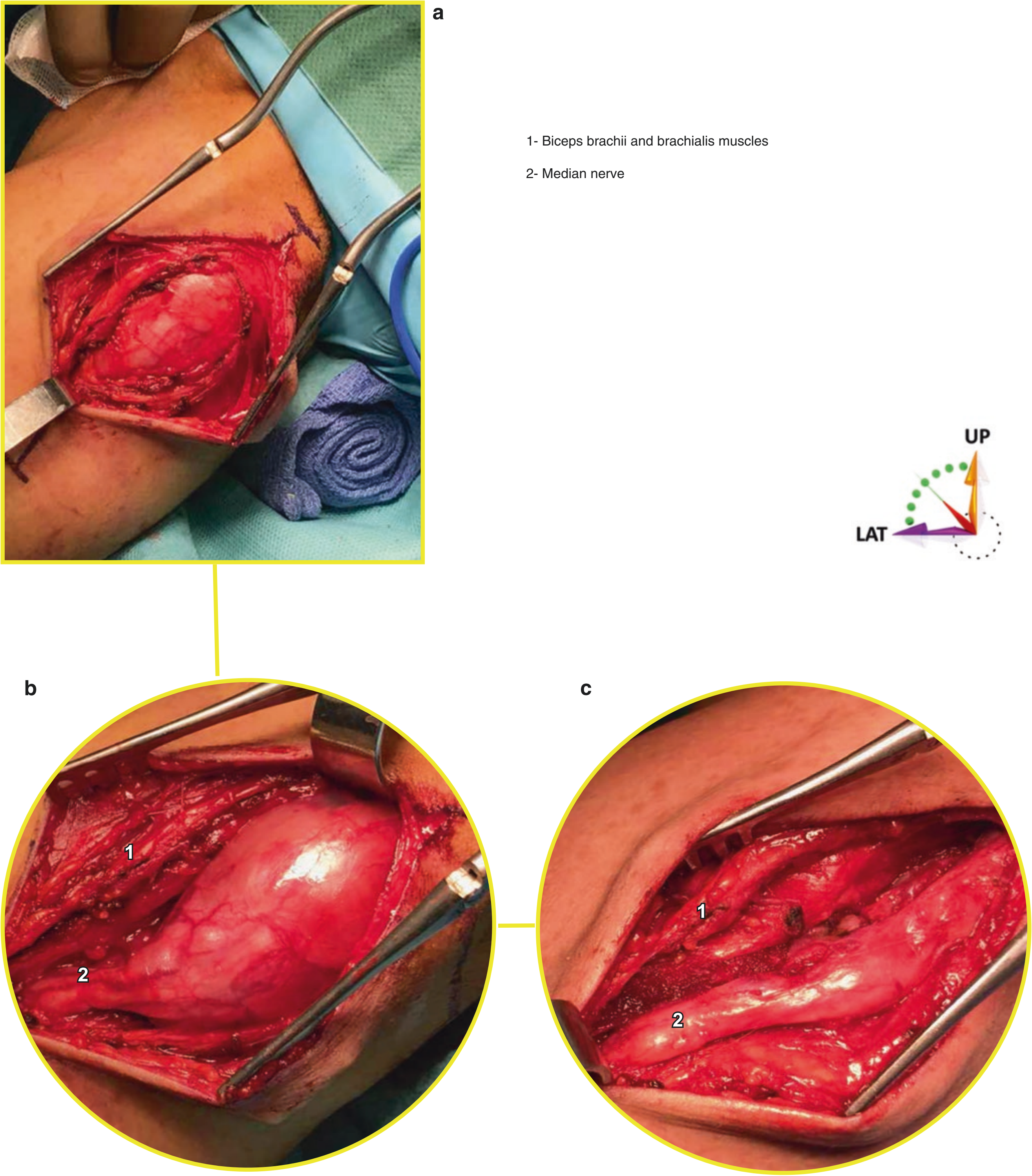

a
1- Biceps brachii and brachialis muscles
2- Median nerve
UP
LAT
b
1
2
c
1
2

Figure M38. Median nerve neuroma in the arm. (**a**) Visualization of the neuroma after incision and passage of aponeurosis. (**b**) Median nerve with a swollen appearance in relation to oedematous inflammatory changes. (**c**) Extracted neuroma with preserved median nerve.

The Axillary Nerve

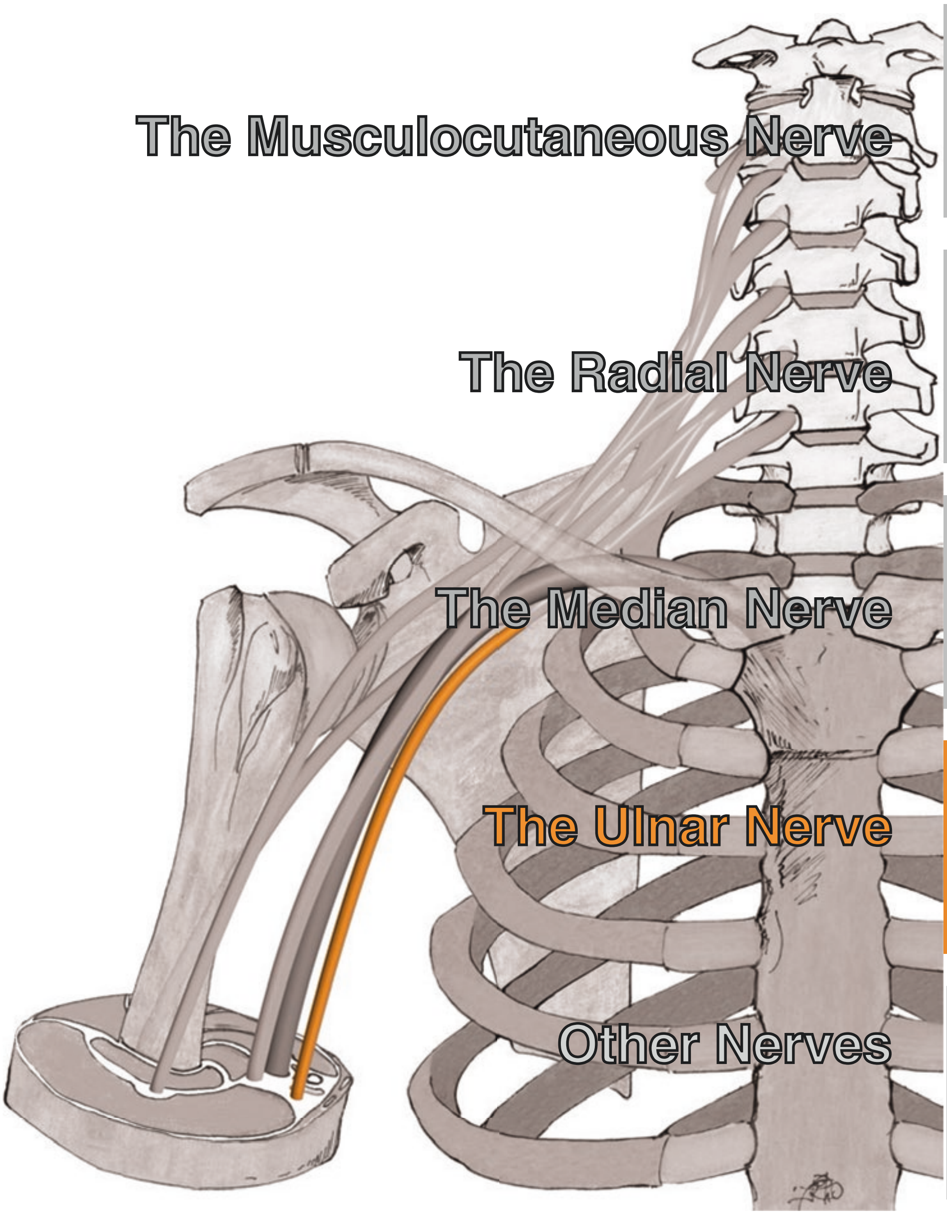
The Musculocutaneous Nerve

The Radial Nerve

The Median Nerve

The Ulnar Nerve

Other Nerves



The Ulnar Nerve

Morphological Data

The ulnar nerve is a mixed nerve coming from the lower trunk of the brachial plexus.

Origin

It is constituted of the C8, T1 and sometimes C7 roots (Figures U1 and U2). They unite in order to form the lower trunk of the brachial plexus. The medial cord comes from the anterior division of this trunk. The ulnar nerve is a terminal branch of the medial cord that also gives off the medial root of the median nerve and the medial cutaneous nerves of the arm and forearm. The medial cord of the brachial plexus splits medially to the axillary artery to give off the medial root of the median nerve and the ulnar nerve. The ulnar nerve then faces the median nerve laterally and above, the latter's roots join again a few centimetres below (Figure U3).

The axillary vein is situated medially beside the ulnar nerve, which is initially situated between the axillary artery and nerve.

Path

In the arm, the ulnar nerve is situated medially beside the axillary artery and then beside the brachial artery and initially faces the radial and medial nerve laterally, the medial cutaneous nerve of the arm medially and the axillary vein. It then rests in behind on the long head of the triceps brachii and faces the coracobrachialis muscle laterally (Figure U3).

The ulnar nerve stays in contact with the brachial artery until the middle third of the arm in the medial brachial canal; it then separates from it by going through the medial intermuscular septum.

It is then situated in the posterior compartment of the arm and lies against the medial head of the triceps brachii (Figure U4).

In the elbow, it goes towards the medial epicondyle, accompanied by the superior ulnar collateral artery, and then into the epitrochlear-olecranon groove. After this groove, it goes between the two heads of the flexor carpi ulnaris muscle, which is often the point where it gets compressed in the elbow (Figures U5, U6 and U16).

At the level of the superior half of the forearm, it is situated between the flexor carpi ulnaris and the flexor digitorum profundus.

It then becomes more superficial and travels along the medial edge of the ulnar artery until the wrist (Figures U8, U18 and U19). It gives rise to the dorsal cutaneous branch in the hand, a few centimetres above the wrist, and then penetrates into the hand in front of the flexor retinaculum and outside of the pisiform bone (Figure U9).

This tunnel is referred to as Guyon's canal or ulnar canal in the Nomina Anatomica. The limits of the ulnar canal are mainly constituted by an expansion of the flexor retinaculum. The latter splits in two; on the one hand, it fuses with the tendon of the flexor carpi ulnaris before joining onto the pisiform bone and then forms the canal's arch. On the other hand, it widens deeper and constitutes a deep expansion of the retinaculum, which covers the carpal bones and inserts itself on the pisiform, hamulus and hamate bones. This is a resistant quadrilateral plate made of transversal fibres, higher on the outside than on the inside; this part composes the base of the canal. Its medial limit is successively comprised of the insertion tendon of the flexor carpi ulnaris on the pisiform bone and then of the proximal part of the insertion tendon of the abductor digiti minimi (Figure U9).

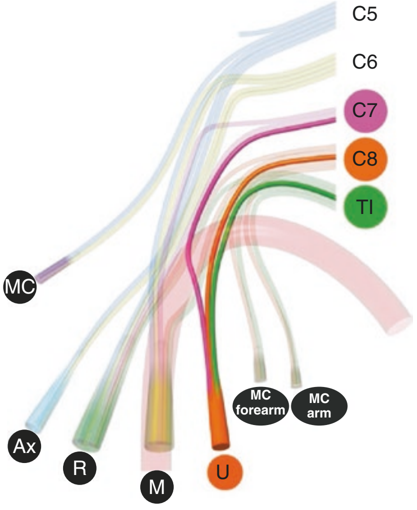


Figure U1. Origin of the ulnar nerve.

Electronic Supplementary Material The online version of this chapter (https://doi.org/10.1007/978-3-030-49179-6_9) contains supplementary material, which is available to authorized users.

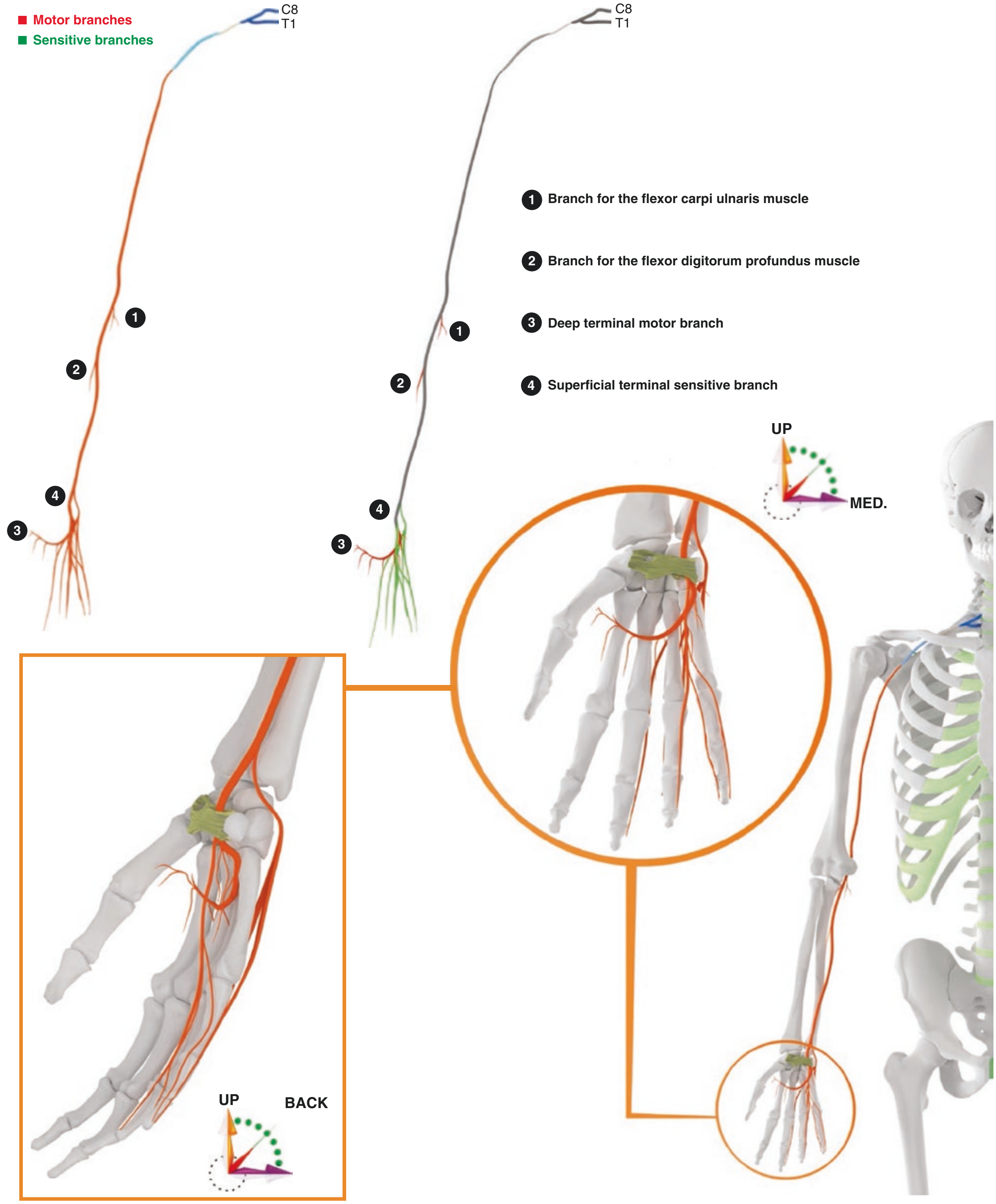
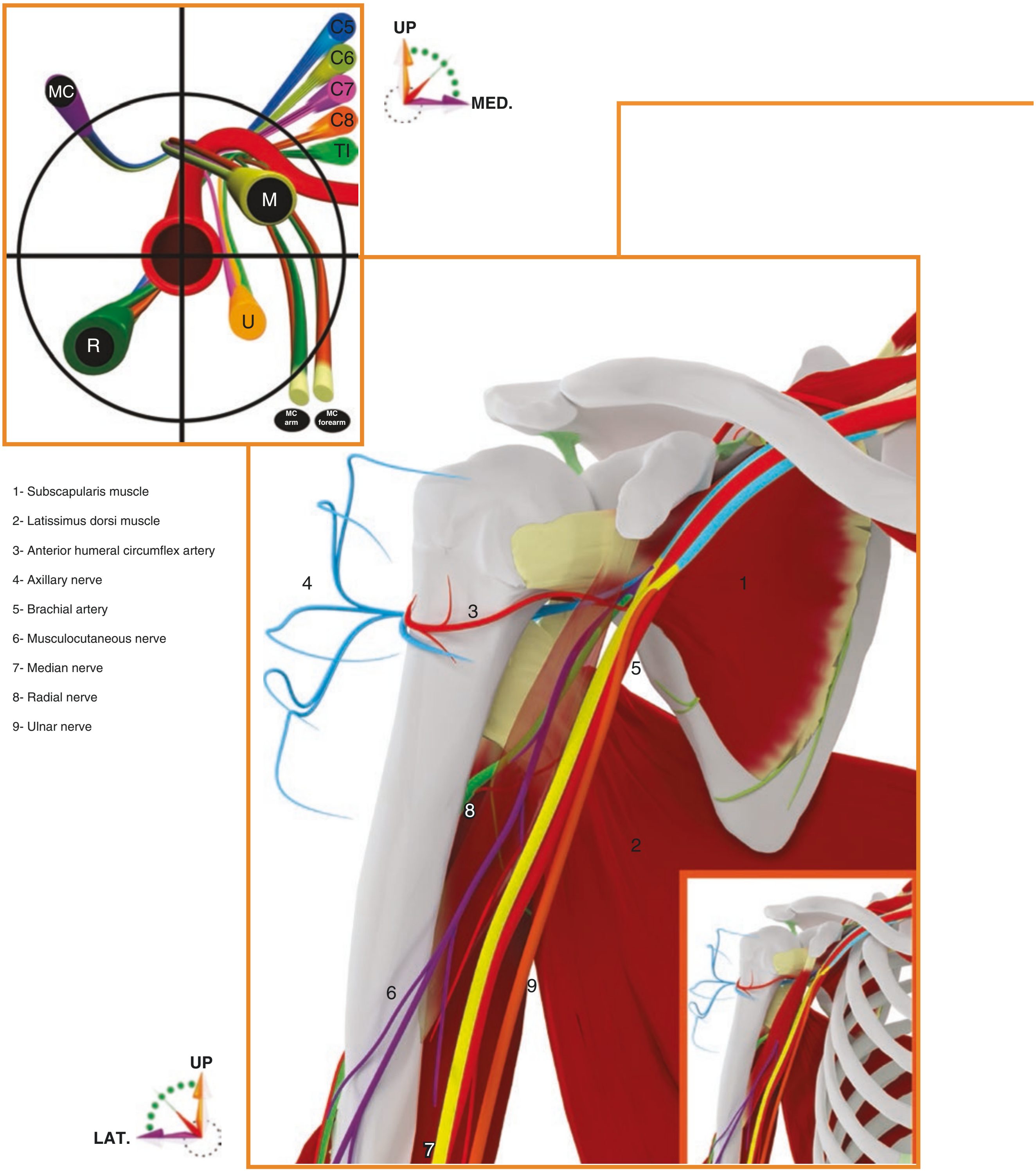

■ Motor branches
■ Sensitive branches
C8
T1
1
2
3
4
C8
T1
1
2
3
4
1 Branch for the flexor carpi ulnaris muscle
2 Branch for the flexor digitorum profundus muscle
3 Deep terminal motor branch
4 Superficial terminal sensitive branch
UP
MED.
UP
BACK

Figure U2. Distribution of the ulnar nerve and its relations with bones.


C5
C6
C7
C8
TI
MC
M
U
R
MC arm
MC forearm
UP
MED.
UP
LAT.
4
3
1
5
8
2
6
9
7

1- Subscapularis muscle
2- Latissimus dorsi muscle
3- Anterior humeral circumflex artery
4- Axillary nerve
5- Brachial artery
6- Musculocutaneous nerve
7- Median nerve
8- Radial nerve
9- Ulnar nerve

Figure U3. Neurovascular relations of the ulnar nerve in the arm.

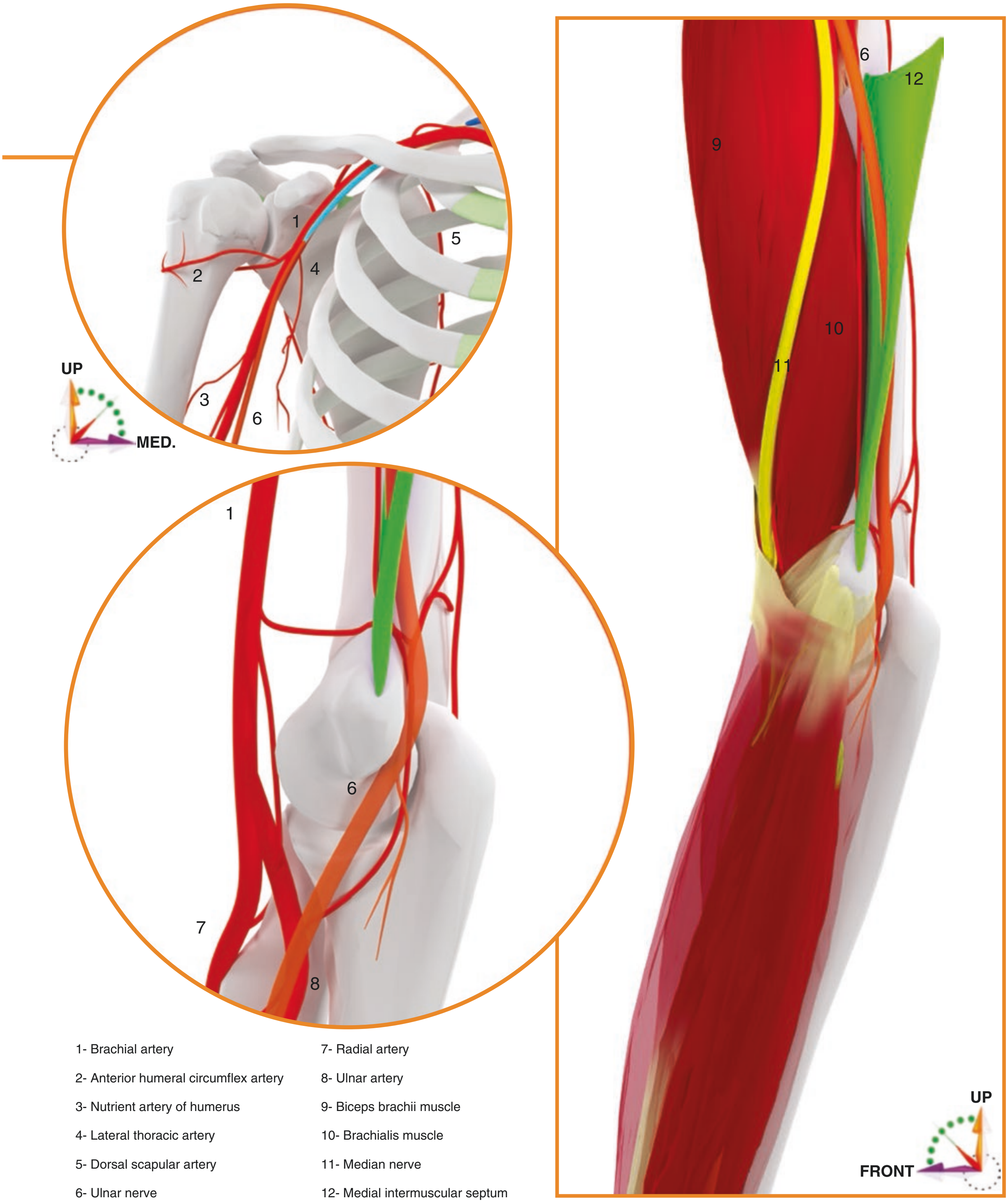
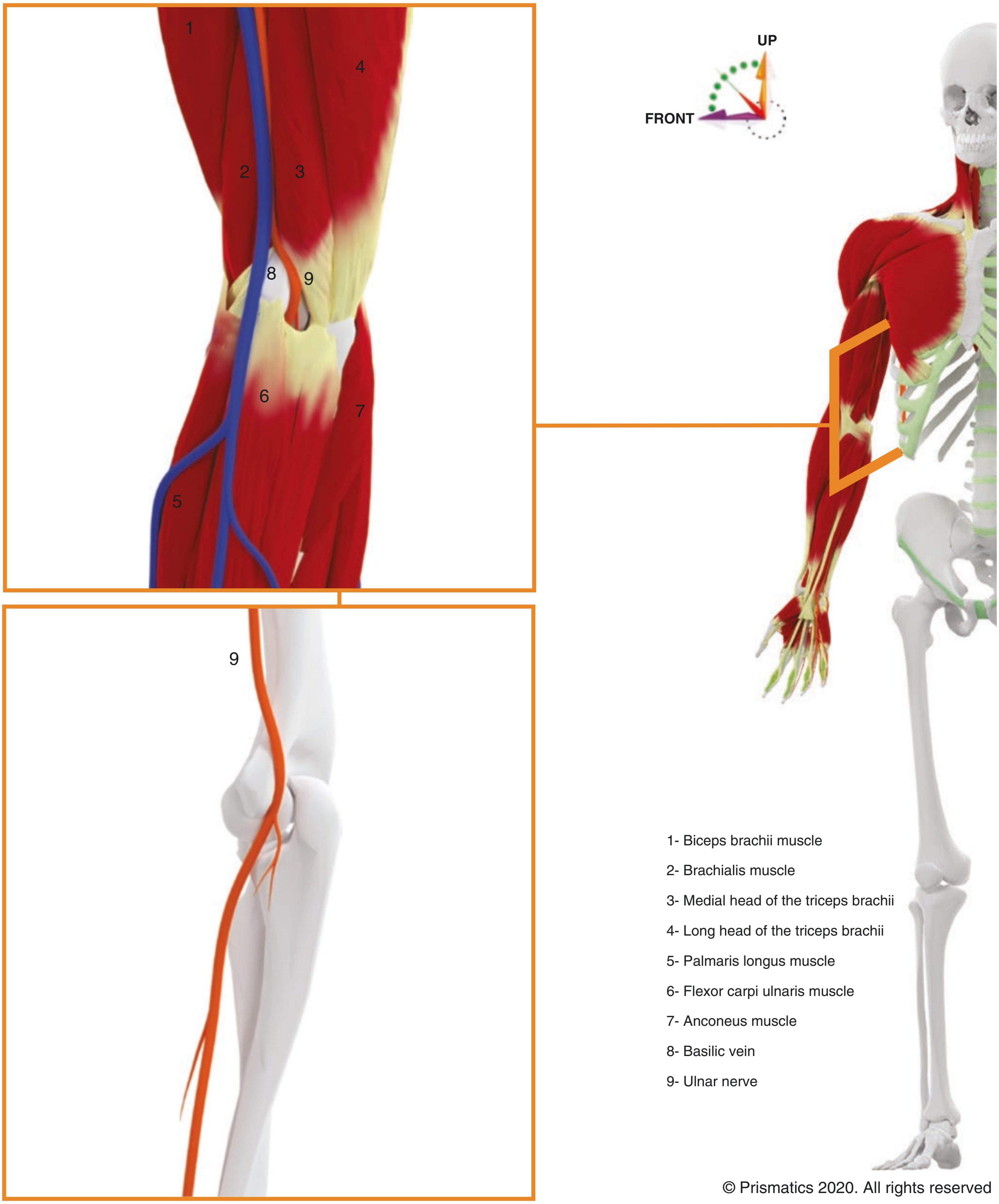

1
2
3
4
5
6
UP
MED.
1
6
7
8
6
12
9
10
11
UP
FRONT
1- Brachial artery
2- Anterior humeral circumflex artery
3- Nutrient artery of humerus
4- Lateral thoracic artery
5- Dorsal scapular artery
6- Ulnar nerve
7- Radial artery
8- Ulnar artery
9- Biceps brachii muscle
10- Brachialis muscle
11- Median nerve
12- Medial intermuscular septum

Figure U4. Neurovascular relations of the ulnar nerve in the elbow.



1- Biceps brachii muscle
2- Brachialis muscle
3- Medial head of the triceps brachii
4- Long head of the triceps brachii
5- Palmaris longus muscle
6- Flexor carpi ulnaris muscle
7- Anconeus muscle
8- Basilic vein
9- Ulnar nerve

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Figure U5. Muscular relations of the ulnar nerve in the elbow (medial view).

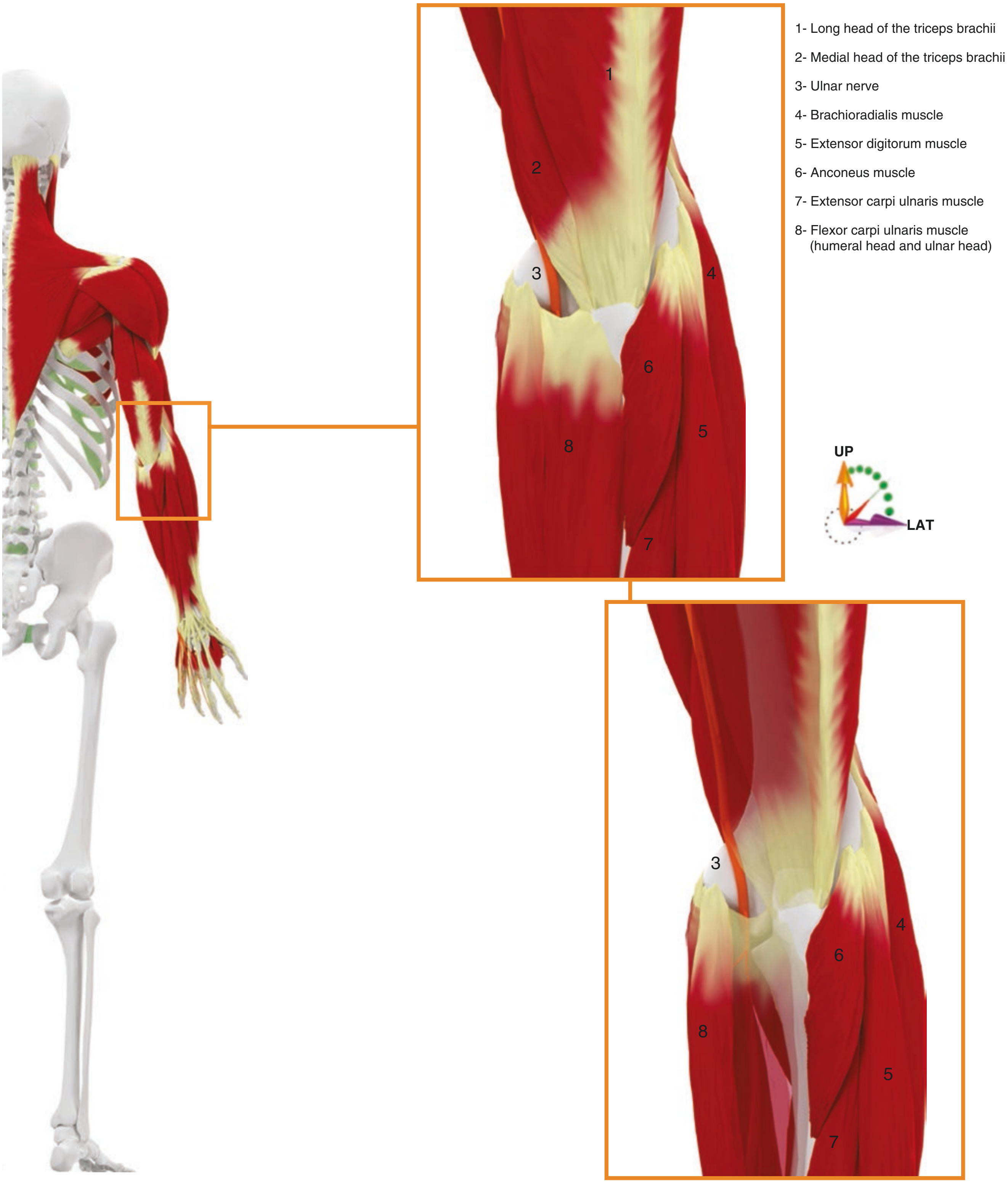
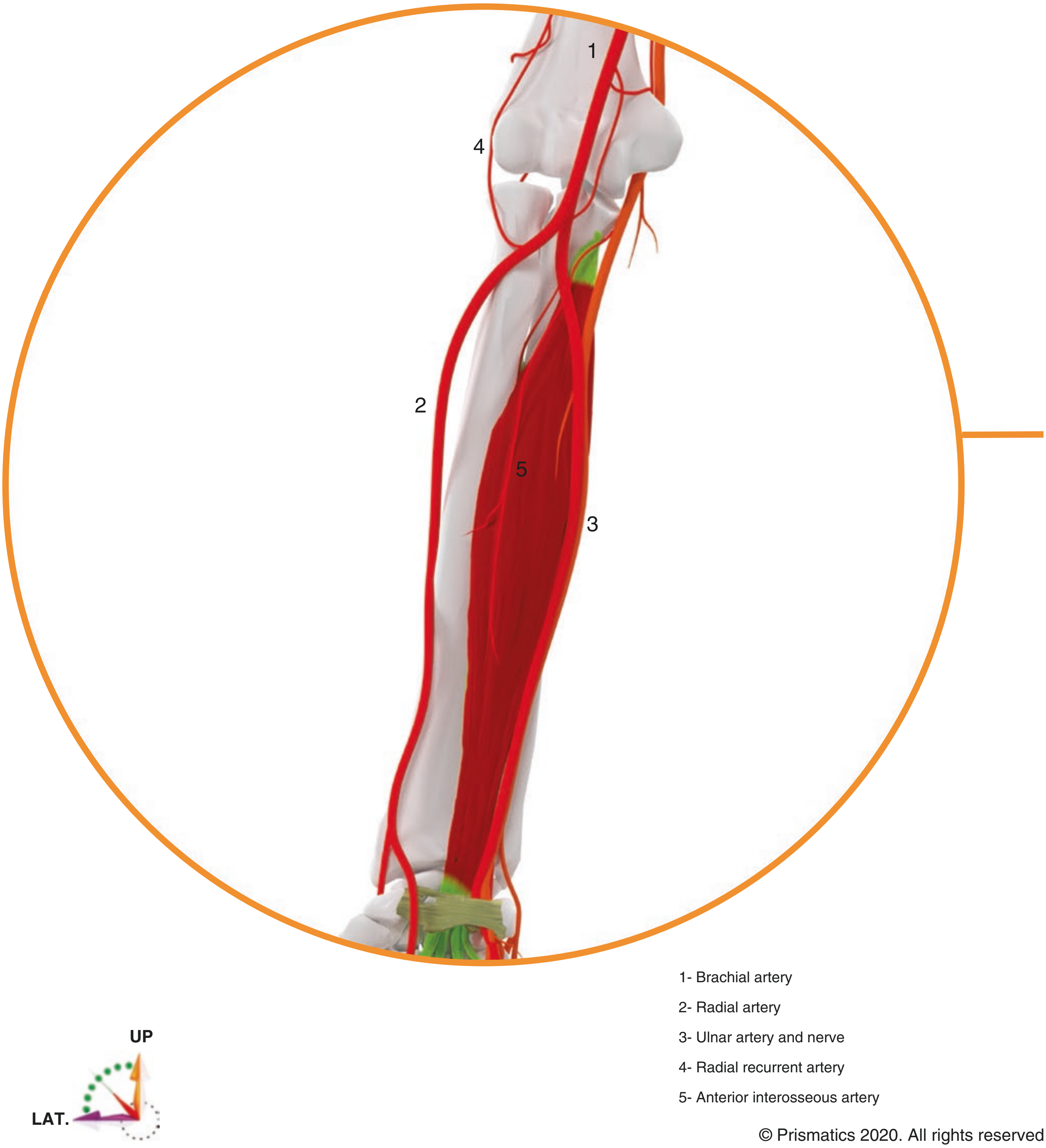

1
2
3
4
6
8
5
7
3
4
6
8
5
7
1- Long head of the triceps brachii
2- Medial head of the triceps brachii
3- Ulnar nerve
4- Brachioradialis muscle
5- Extensor digitorum muscle
6- Anconeus muscle
7- Extensor carpi ulnaris muscle
8- Flexor carpi ulnaris muscle (humeral head and ulnar head)
UP
LAT

Figure U6. Muscular relations of the ulnar nerve in the elbow (posterior view).



1- Brachial artery

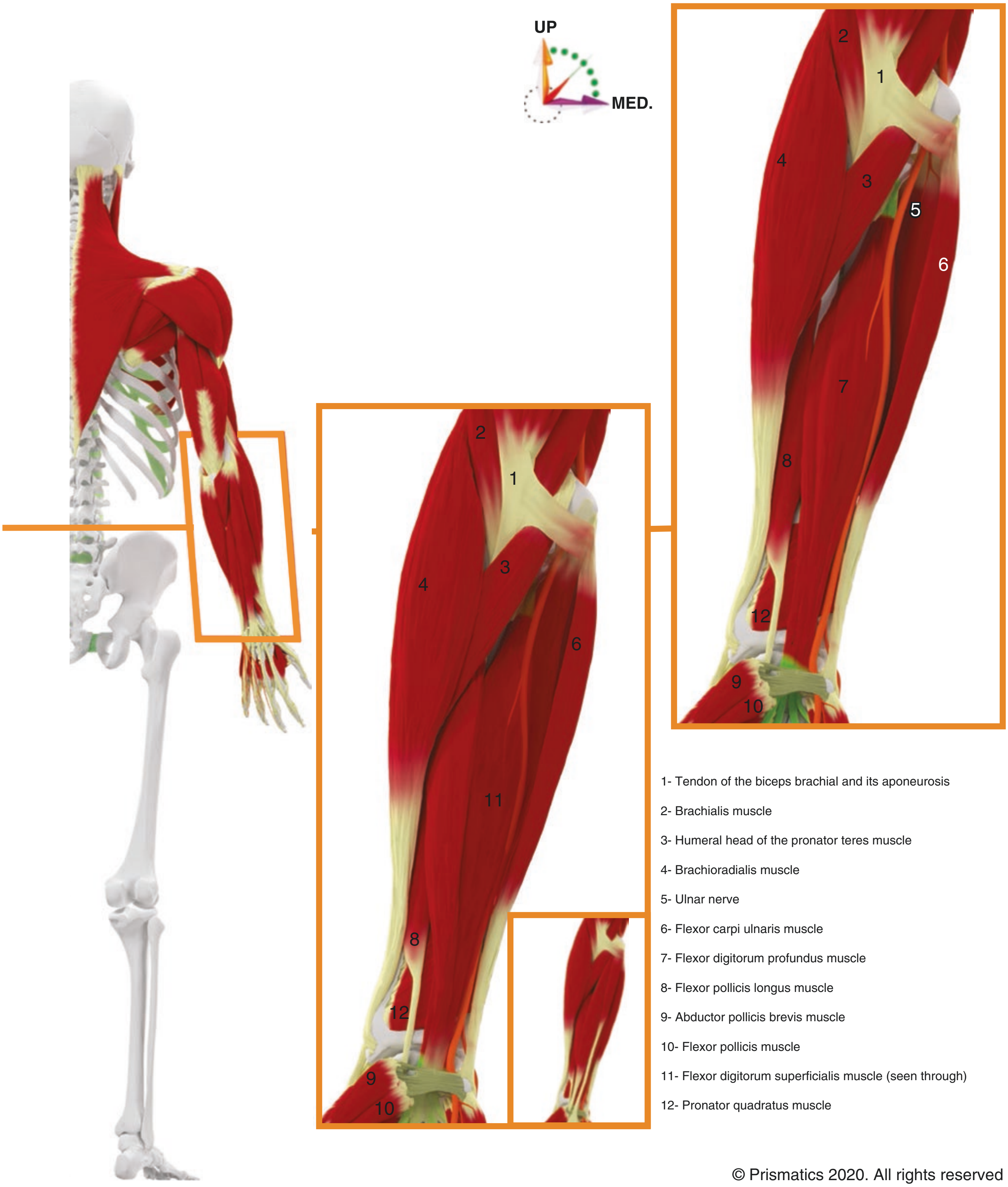
2- Radial artery

3- Ulnar artery and nerve

4- Radial recurrent artery

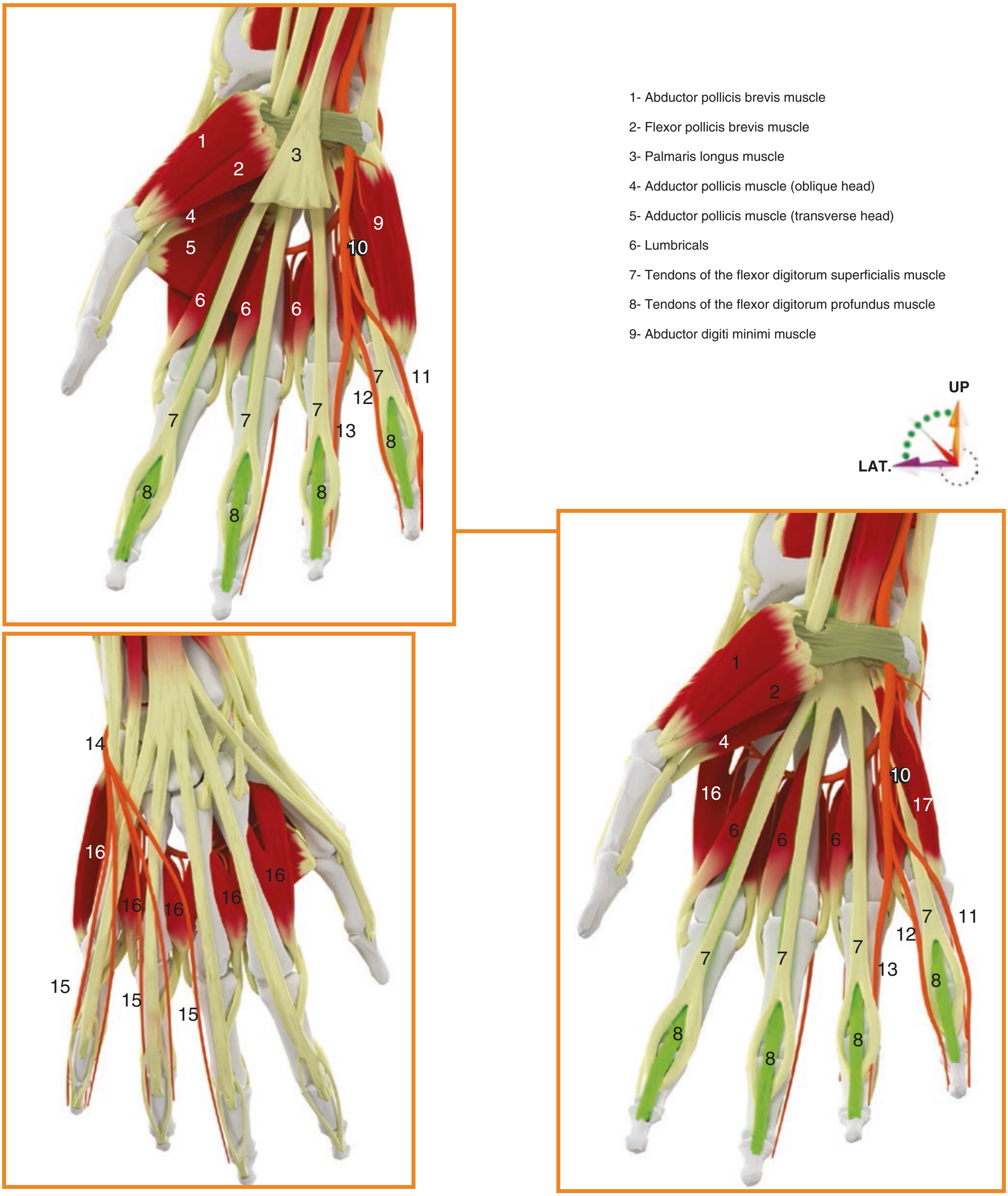
5- Anterior interosseous artery

Figure U7. Neurovascular relations of the ulnar nerve in the forearm.



1- Tendon of the biceps brachial and its aponeurosis
2- Brachialis muscle
3- Humeral head of the pronator teres muscle
4- Brachioradialis muscle
5- Ulnar nerve
6- Flexor carpi ulnaris muscle
7- Flexor digitorum profundus muscle
8- Flexor pollicis longus muscle
9- Abductor pollicis brevis muscle
10- Flexor pollicis muscle
11- Flexor digitorum superficialis muscle (seen through)
12- Pronator quadratus muscle

Figure U8. Muscular relations of the ulnar nerve in the forearm (anterior view).


1
2
3
4
9
5
10
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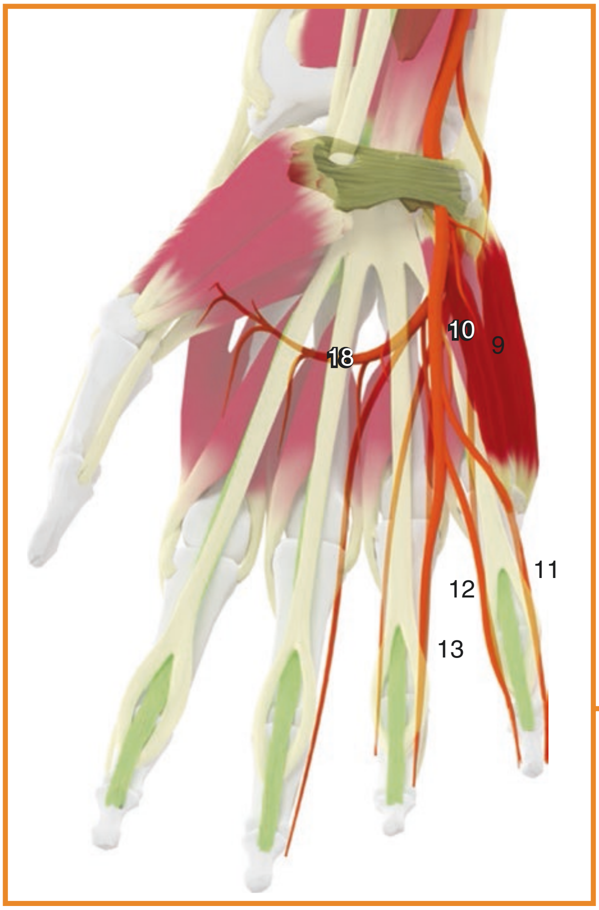
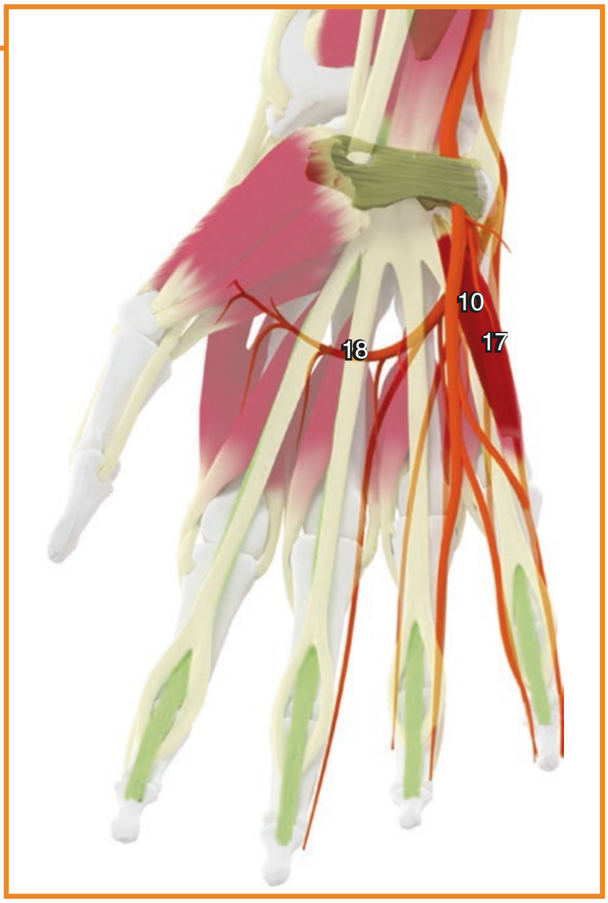
6
6
7
11
12
7
7
7
13
8
8
8
8
UP
LAT.
14
16
16
16
16
16
16
15
15
15
1
2
4
10
16
17
6
6
6
7
11
12
7
7
7
13
8
8
8
8

1- Abductor pollicis brevis muscle
2- Flexor pollicis brevis muscle
3- Palmaris longus muscle
4- Adductor pollicis muscle (oblique head)
5- Adductor pollicis muscle (transverse head)
6- Lumbricals
7- Tendons of the flexor digitorum superficialis muscle
8- Tendons of the flexor digitorum profundus muscle
9- Abductor digiti minimi muscle

Figure U9. Muscular relations and distribution of the ulnar nerve in the hand (sensitive branches).





10- Superficial branch of the ulnar nerve
11- Medial proper palmar digital nerve of the little finger
12- Lateral palmar digital nerve of the little finger
13- Medial proper palmar digital nerve of the ring finger
14- Dorsal branch of the ulnar nerve
15- Dorsal digital nerves
16- Dorsal interossei muscles
17- Opponens digiti minimi muscle
18- Deep branch of the ulnar nerve

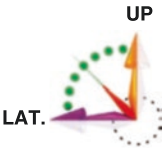


Figure U10. Muscular relations and distribution of the ulnar nerve in the hand (motor branches).

Neurovascular Relations

At its origin, the ulnar nerve faces the axillary artery laterally and the axillary vein medially. At the level of the axillary fossa, the subscapular artery crosses in front of the ulnar nerve.

The ulnar nerve is then placed medially related to the brachial artery in the arm (Figures U3, U12 and U14). In the inferior part of the arm, the ulnar nerve parts with the brachial artery and goes through the medial intermuscular septum before following the path of the superior ulnar collateral artery (Figure U4). At the level of the elbow, it goes away from this artery and places itself behind the basilic vein. In the forearm, the ulnar nerve is placed on the medial face of the ulnar artery until the ulnar canal (Figures U7, U13 and U15).

Collateral Branches

Of note, unlike the musculocutaneous, median and radial nerves, the ulnar nerve does not give off any collateral branch in the arm.

Its collateral branches start from the level of the elbow, with (Figure U2):

- Articular branches
- One branch for the ulnar artery
- Muscular branches in the forearm for the flexor carpi ulnaris and flexor digitorum profundus muscles for its medial part
- Sensitive branches for the dorsal face of the hand, from a main branch that splits off at the inferior third of the forearm, as well as a palmar branch for the hypothenar eminence

Terminal Branches

The ulnar nerve splits into two terminal branches, a superficial branch and a deep branch, at the level of the wrist.

The superficial branch is sensitive and gives off the medial and lateral palmar collateral cutaneous nerve of the fifth finger and medial palmar collateral cutaneous nerve of the fourth finger. The last two form the digital nerves of the fourth interdigital spaces.

The deep branch is a motor branch that heads towards the dorsal and palmar interossei muscles of the hand and for the third and fourth lumbricals. It also innervates the abductor, opponens and flexor digiti minimi brevis, the adductor pollicis and the deep head of the flexor pollicis brevis as well as the deep palmar arch. This branch sinks directly from its origin into the arch formed by the pisiform and hamulus bones. It goes between the abductor digiti minimi and opponens digiti minimi and then adopts a path transversal to the deep face of the tendons of the flexor digitorum muscles, under the lumbricals, but on the dorsal face of the interossei muscles (Figures U9 and U10).

Motor Function

Its motor innervation includes the flexor carpi ulnaris and the ulnar half of the flexor digitorum profundus. It also innervates all of the intrinsic muscles of the hand except for the first and second lumbricals, the abductor pollicis brevis and the opponens pollicis. Finally, the flexor pollicis brevis is innervated in a mixed way by the median and the ulnar nerves in variable proportion.

Therefore, the ulnar nerve takes care of the function of adduction of the hand as well as the flexion of the fingers on the hand in a partial way. It also allows prehensility and the spreading apart of the fingers (Figure U11).

Sensitive Function

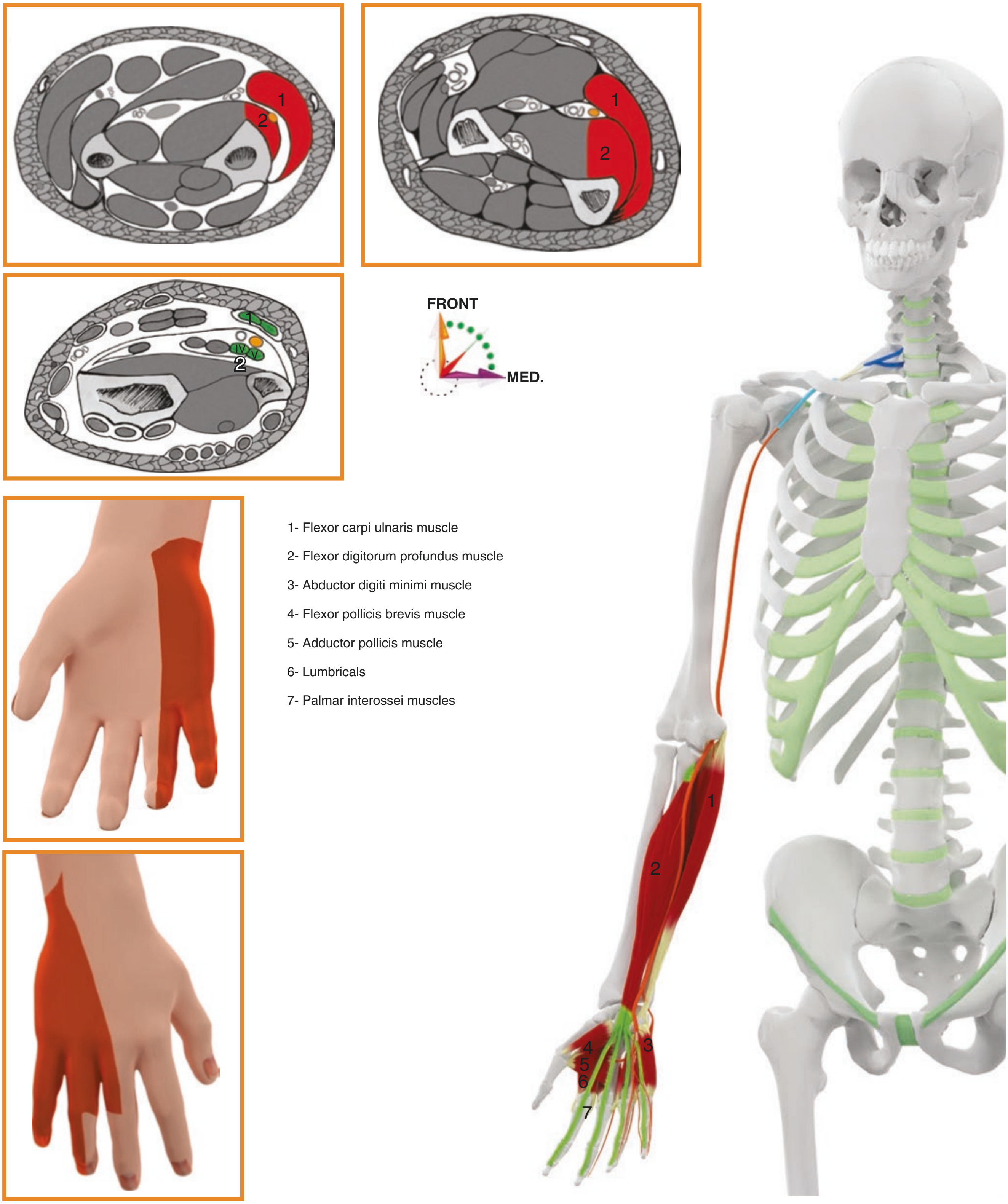
The cutaneous sensitive area of the ulnar nerve corresponds to the ulnar part of the palm of the hand, except for the little finger's axis. This distribution of the innervations of the palmar face between the median and the ulnar nerves can vary according to the four main types described in 1988 by G.P. Ferrari. The dorsal face of the hand includes the whole little finger, the proximal phalanx, the medial halves of the intermediate and distal phalanx of the ring finger and the medial half of the proximal phalanx of the middle finger according to a line separating the dorsal face of the hand in two halves (Figure U11).

Anastomoses

The median nerve makes anastomoses with:

- The medial cutaneous nerve of the arm.
- The radial nerve on the dorsal face of the hand.
- And the median nerve several times: a superficial branch between the third and fourth common palmar digital nerves (going either above or below the superficial palmar arch) and a deep branch going through the flexor pollicis brevis called the Riche-Cannieu anastomosis. Another anastomotic branch with the median nerve is frequently described but only sometimes found: the Martin-Grüber anastomosis. It is generally identified in the forearm or shortly after the ulnar canal.

These anastomoses are important to know, especially for their subsequent implications in reconstruction surgeries of this nerve.



1- Flexor carpi ulnaris muscle

2- Flexor digitorum profundus muscle

3- Abductor digiti minimi muscle

4- Flexor pollicis brevis muscle

5- Adductor pollicis muscle

6- Lumbricals

7- Palmar interossei muscles

Figure U11. Motor and sensitive innervation of the ulnar nerve.

1- Pectoralis major muscle

2- Pectoralis minor muscle

3- Cephalic vein

4- Deltoid muscle

5- Short head of the biceps brachii muscle

6- Coracobrachialis muscle

7- Tendon of the long head of the biceps brachii muscle

8- Latissimus dorsi muscle

9- Humerus

10- Teres major muscle

11- Lateral head of the triceps brachii muscle

12- Circumflex artery and nerve

13- Long head of the triceps brachii muscle

14- Teres minor muscle

15- Infraspinatus muscle

16- Scapula

17- Medial cutaneous nerve of arm

18- Median nerve

19- Medial cutaneous nerve of forearm

20- Ulnar nerve

21- Radial nerve

22- Musculocutaneous nerve

23- Subscapularis muscle

24- Brachial vein

25- Brachial artery

26- Serratus anterior

27- Biceps brachii muscle

28- Brachialis muscle

29- Brachioradialis muscle

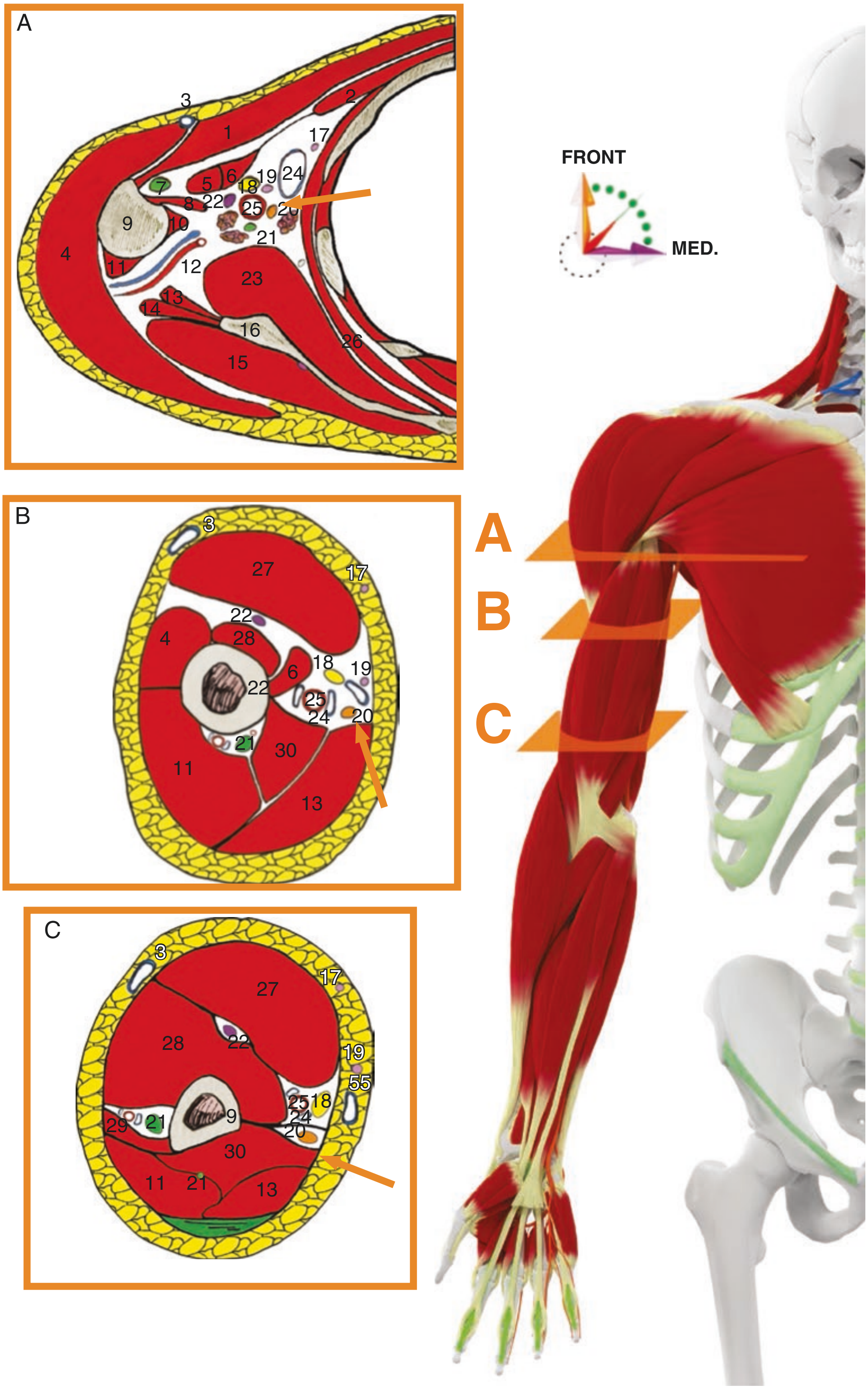

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Figure U12. Relations of the ulnar nerve in the arm, axial sections.

30- Medial head of the triceps brachii muscle

31- Extensor carpi radialis longus muscle

32- Extensor carpi radialis brevis muscle

33- Tendon of epicondyle muscles

34- Anconeus muscle

35- Olecranon

36- Tendon of the triceps brachii muscle

37- Tendon of the median epycondylian muscles

38- Pronator teres muscle

39- Ulna

40- Radius

41- Palmaris longus muscle

42- Flexor carpi radialis muscle

43- Flexor digitorum superficialis muscle

44- Flexor digitorum profundus muscle

45- Flexor pollicis longus muscle

46- Flexor carpi ulnaris muscle

47- Abductor pollicis longus muscle

48- Extensor pollicis brevis muscle

49- Extensor pollicis longus muscle

50- Extensor digitorum muscle

51- Extensor digiti minimi muscle

52- Extensor carpi ulnaris muscle

53- Extensor indicis muscle

54- Median vein of the forearm

55- Basilic vein

56- Radial artery and vein

57- Ulnar artery and vein

58- Pronator quadratus muscle

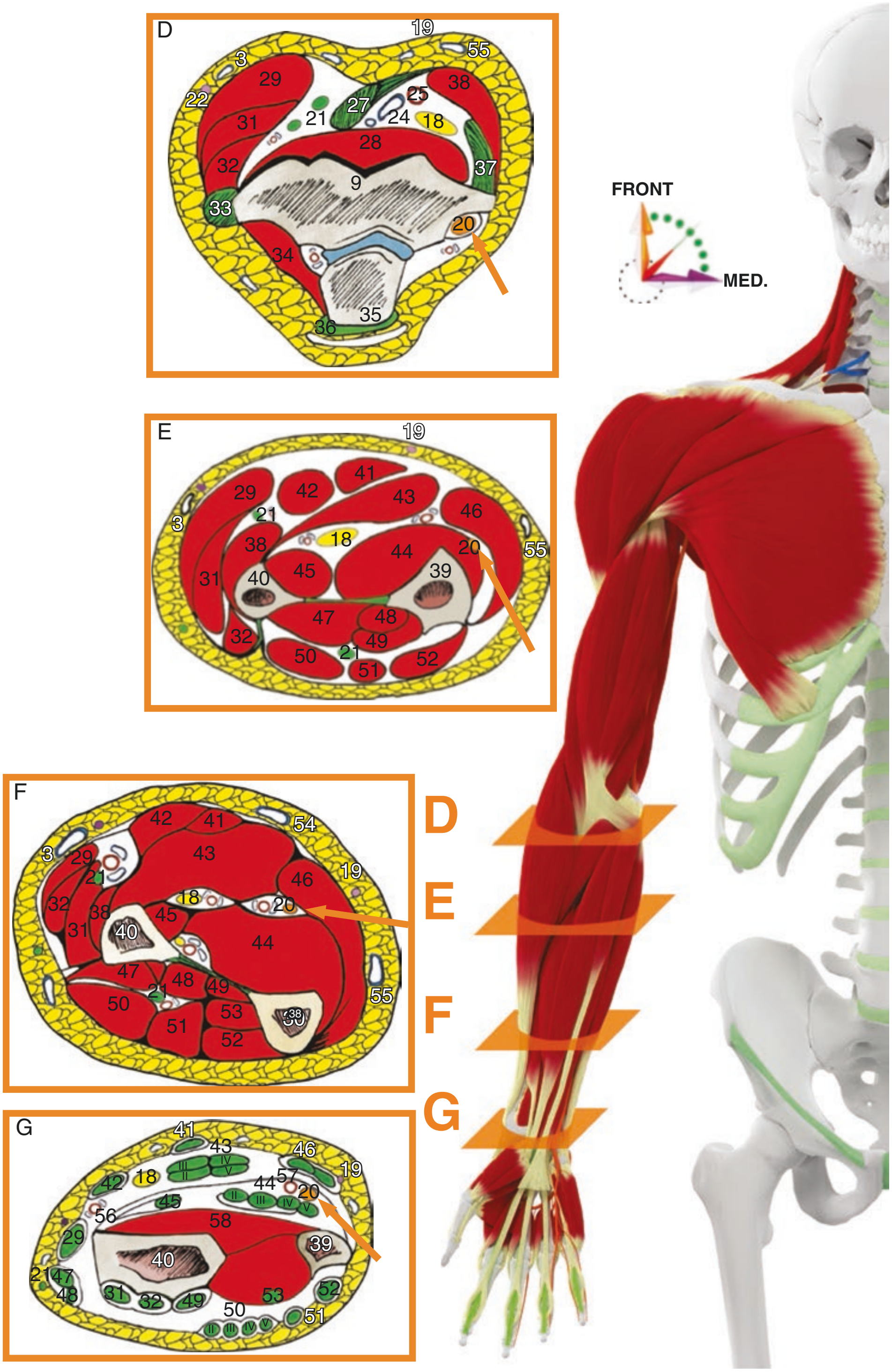
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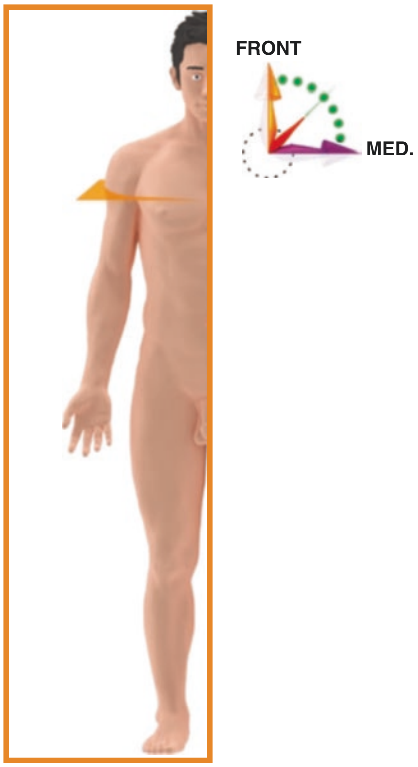
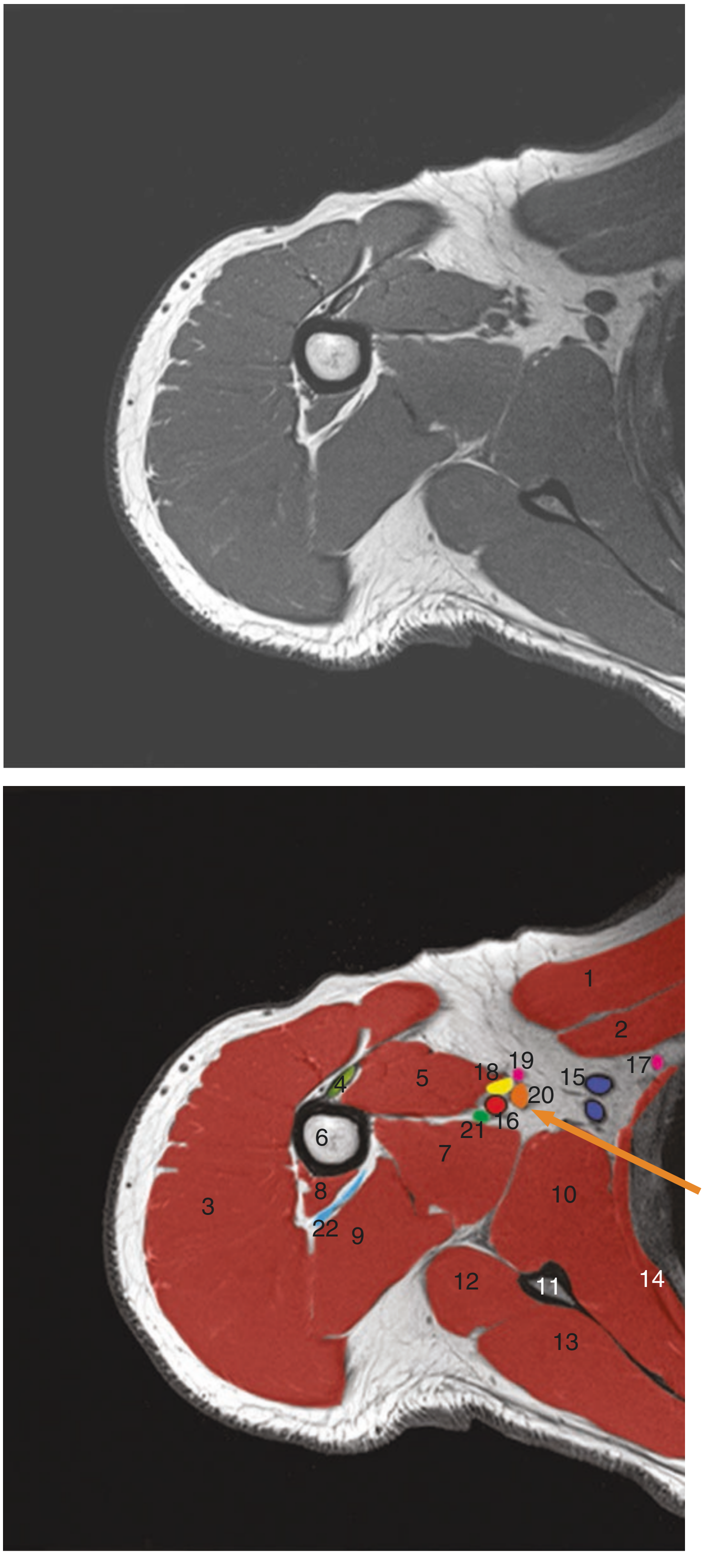
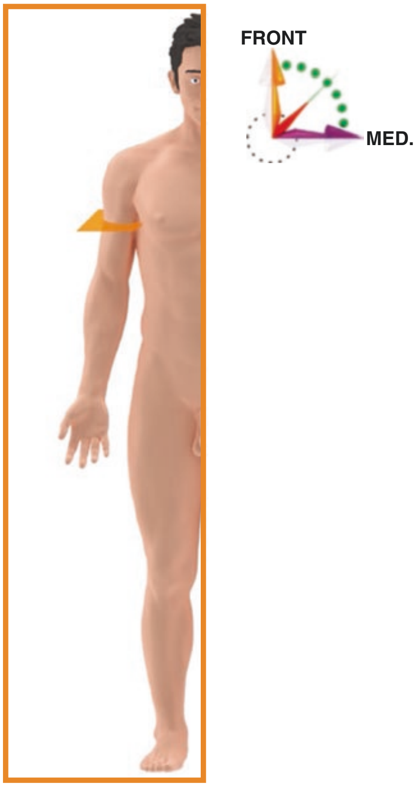
Figure U13. Relations of the ulnar nerve in the elbow and forearm, axial sections.

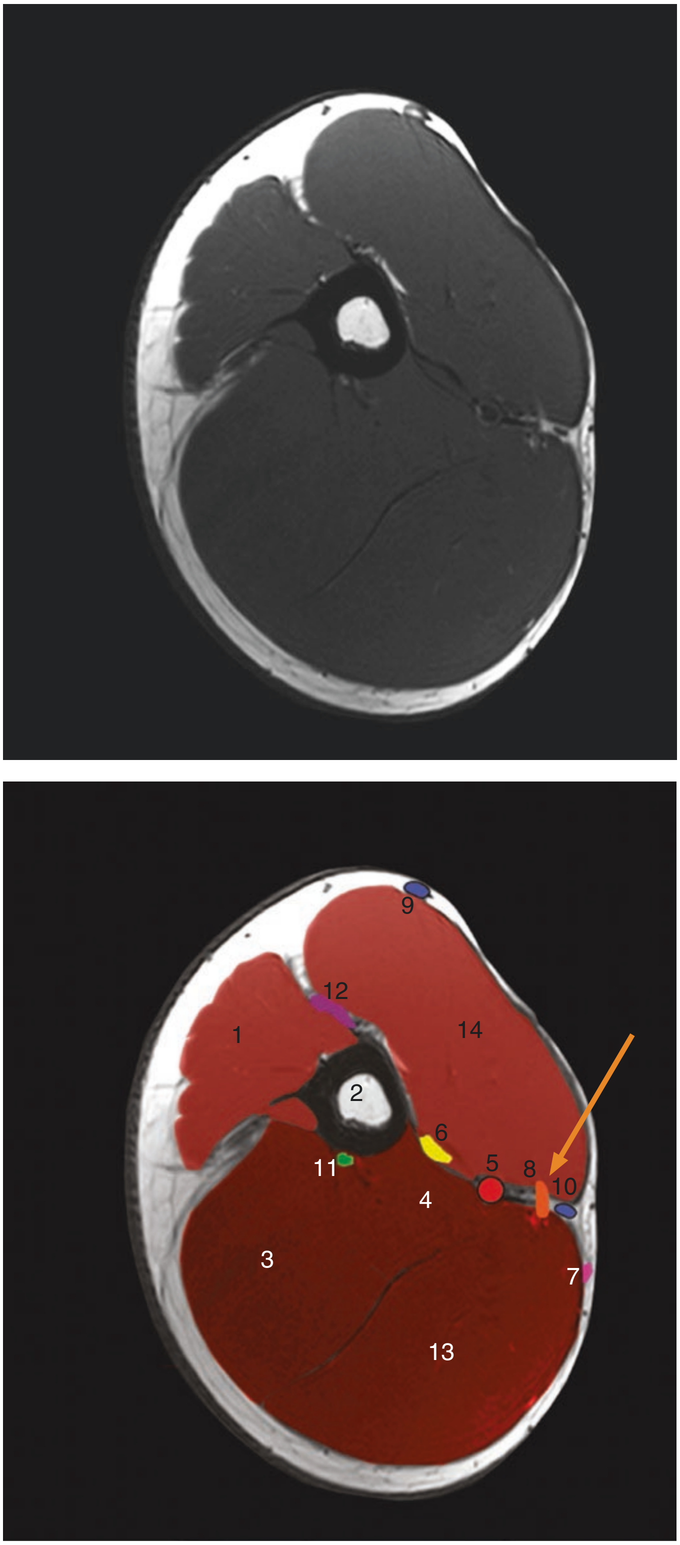




1- Pectoralis major muscle
2- Pectoralis minor muscle
3- Deltoid muscle
4- Long head of the Biceps brachii muscle
5- Latissimus dorsi muscle
6- Humerus
7- Teres major muscle
8- Lateral head of the triceps brachii muscle
9- Medial head of the triceps brachii muscle
10- Subscapularis muscle
11- Scapula
12- Teres minor muscle
13- Infraspinatus muscle
14- Serratus anterior
15- Brachial vein
16- Brachial artery
17- Medial cutaneous nerve of arm
18- Median nerve
19- Medial cutaneous nerve of forearm
20- Ulnar nerve
21- Radial nerve
22- Axillary nerve

Figure U14. MRI scans in the shoulder through the ulnar nerve.





1- Deltoid muscle

2- Humerus

3- Lateral head of the triceps brachii muscle

4- Medial head of the triceps brachii muscle

5- Brachial artery

6- Median nerve

7- Medial cutaneous nerve of forearm

8- Ulnar nerve

9- Cephalic vein

10- Basilic vein

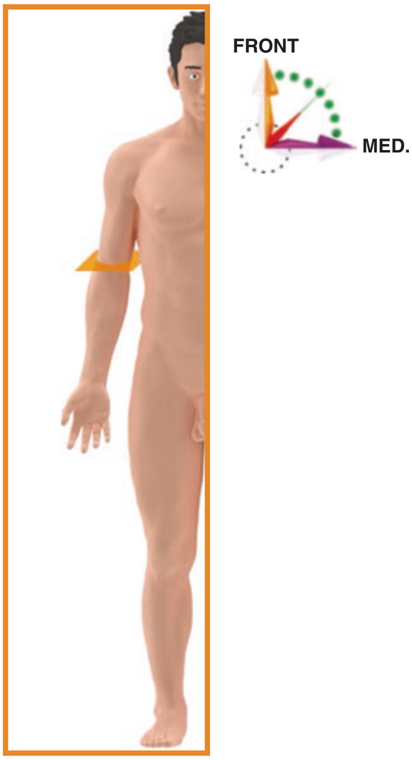
11- Radial nerve

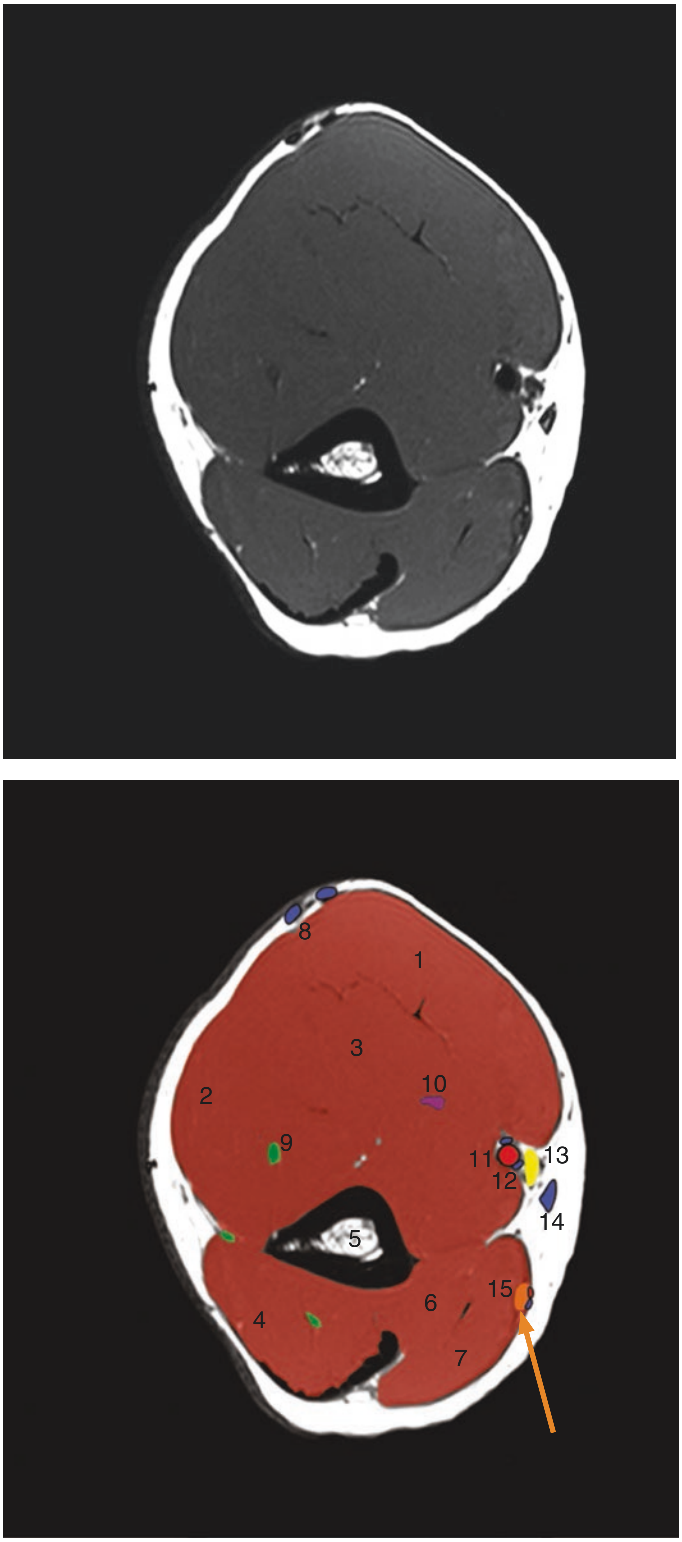
12- Musculocutaneous nerve

13- Long head of the triceps brachii muscle

14- Biceps brachii muscle

Figure U15. MRI scans at the proximal third of the arm through the ulnar nerve.





1- Biceps brachii muscle

2- Brachioradialis muscle

3- Brachialis muscle

4- Lateral head of the triceps brachii muscle

5- Humerus

6- Long head of the triceps brachii muscle

7- Medial head of the triceps brachii muscle

8- Cephalic vein

9- Radial nerve

10- Musculocutaneous nerve

11- Brachial artery

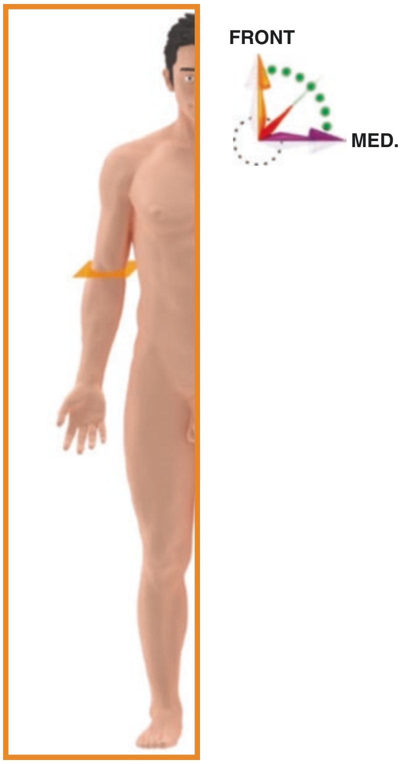
12- Brachial vein

13- Median nerve

14- Basilic vein

15- Ulnar nerve

Figure U16. MRI scans at the distal third of the arm through the ulnar nerve.



1- Brachioradialis muscle

2- Extensor carpi radialis longus muscle

3- Extensor carpi radialis brevis muscle

4- Biceps brachii muscle

5- Tendon of the long head of biceps

6- Brachialis muscle

7- Pronator teres muscle

8- Tendon of the medial epicondylian muscles

9- Humerus

10- Anconeus muscle

11- Ulna

12- Triceps brachii muscle

13- Medial vein at the elbow

14- Brachial vein

15- Brachial artery

16- Median nerve

17- Musculocutaneous nerve

18- Cephalic vein

19- Basilic vein

20- Radial nerve

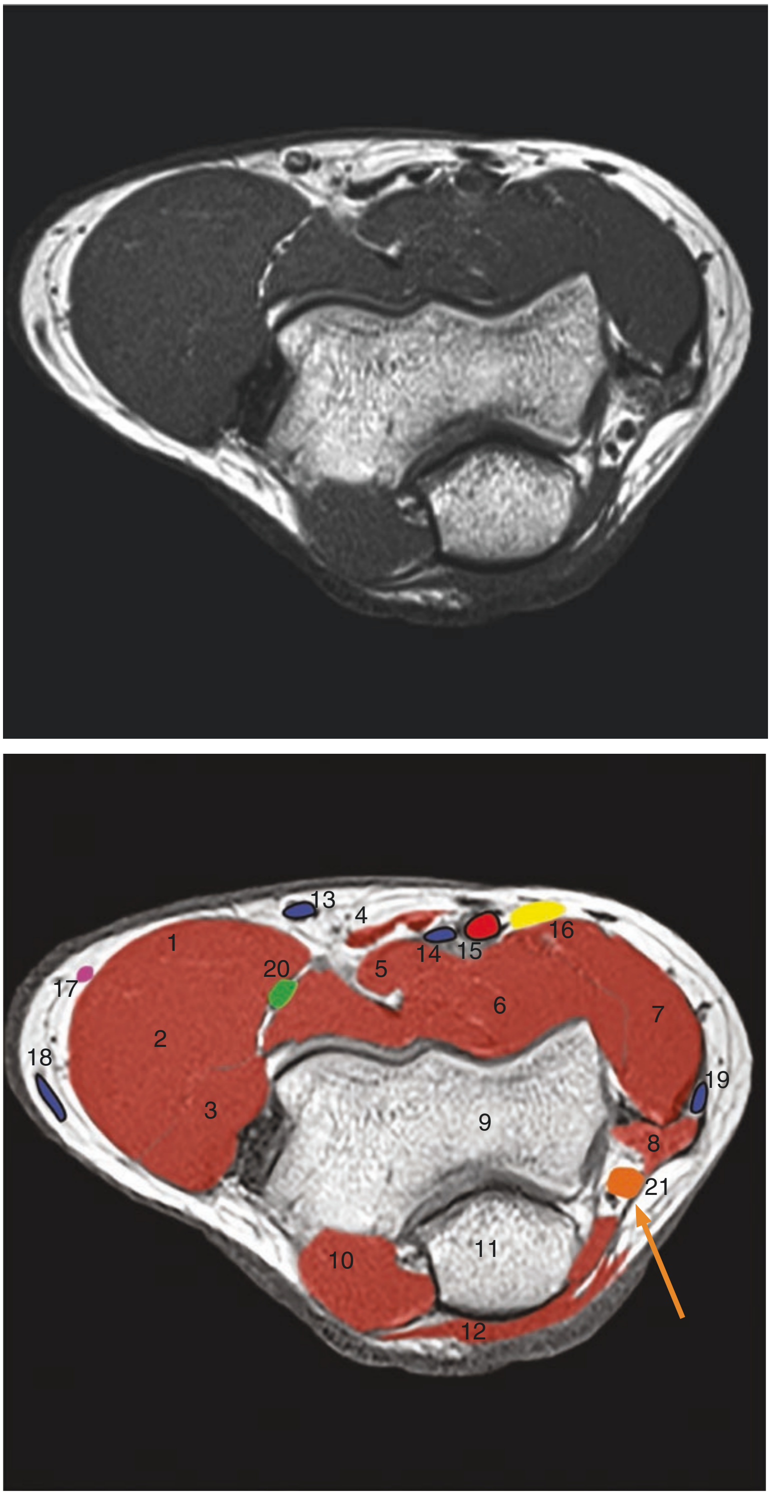
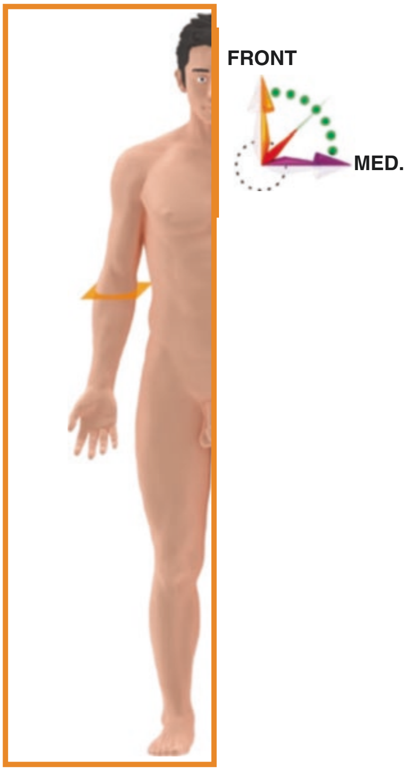
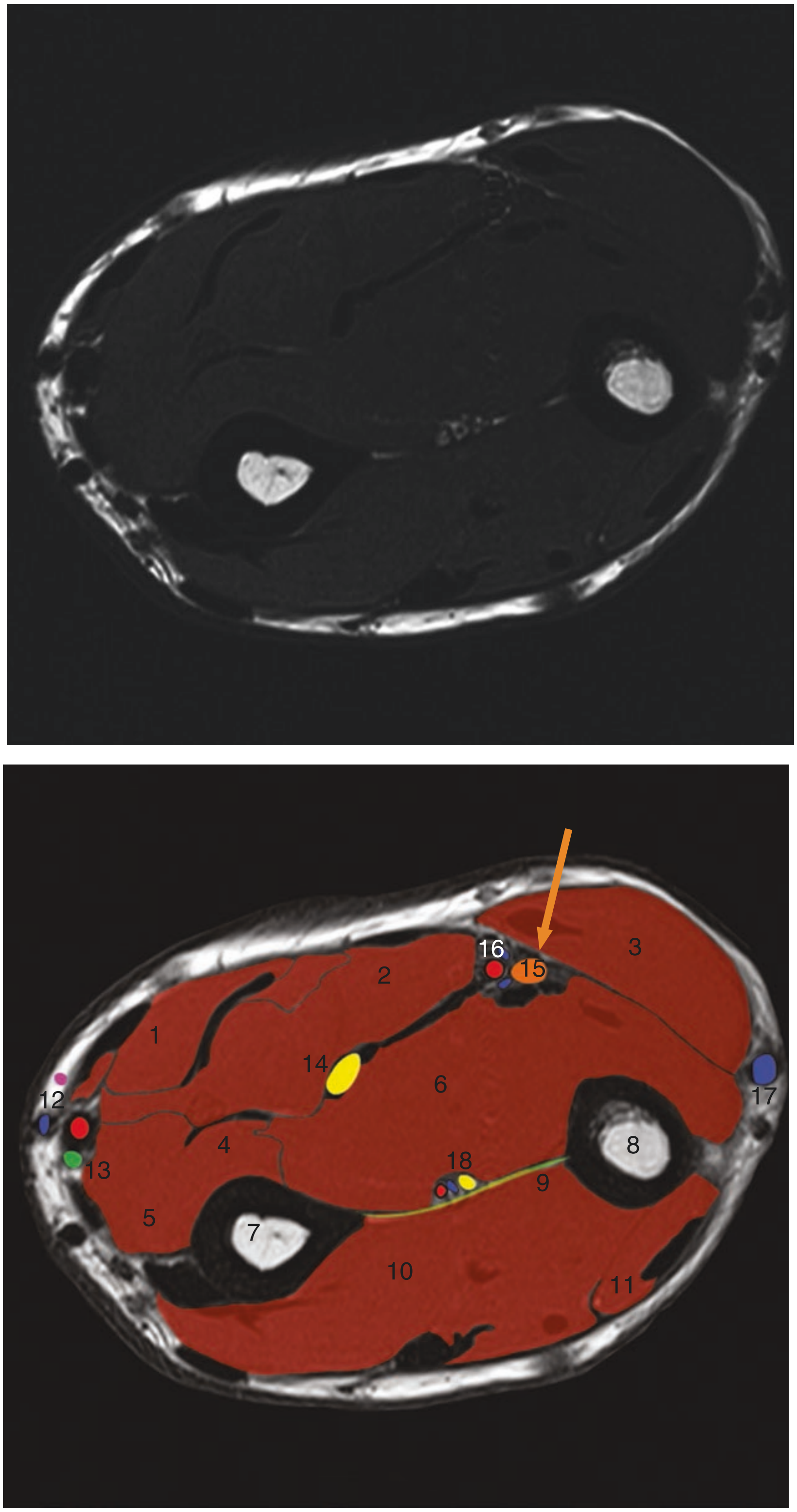


Figure U17. MRI scans in the elbow through the ulnar nerve.





1- Flexor carpi radialis muscle

2- Flexor digitorum superficialis muscle

3- Flexor carpi ulnaris muscle

4- Flexor pollicis longus muscle

5- Extensor carpi radialis brevis muscle

6- Flexor digitorum profundus muscle

7- Radius

8- Ulna

9- Interosseous membrane of the forearm

10- Posterior compartment of the extensor digitorum muscles

11- Extensor carpi muscle

12- Radial artery and vein

13- Radial nerve

14- Median nerve

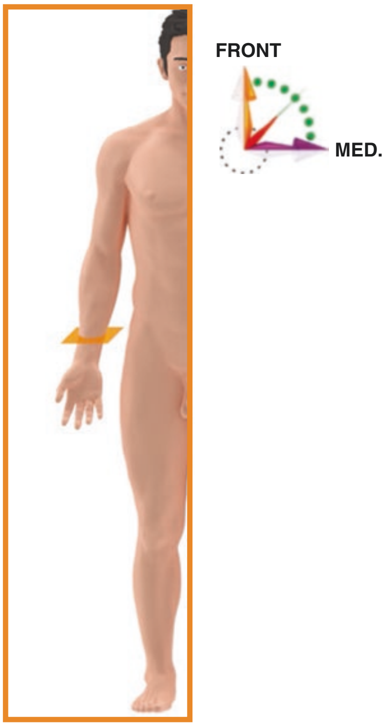
15- Ulnar nerve

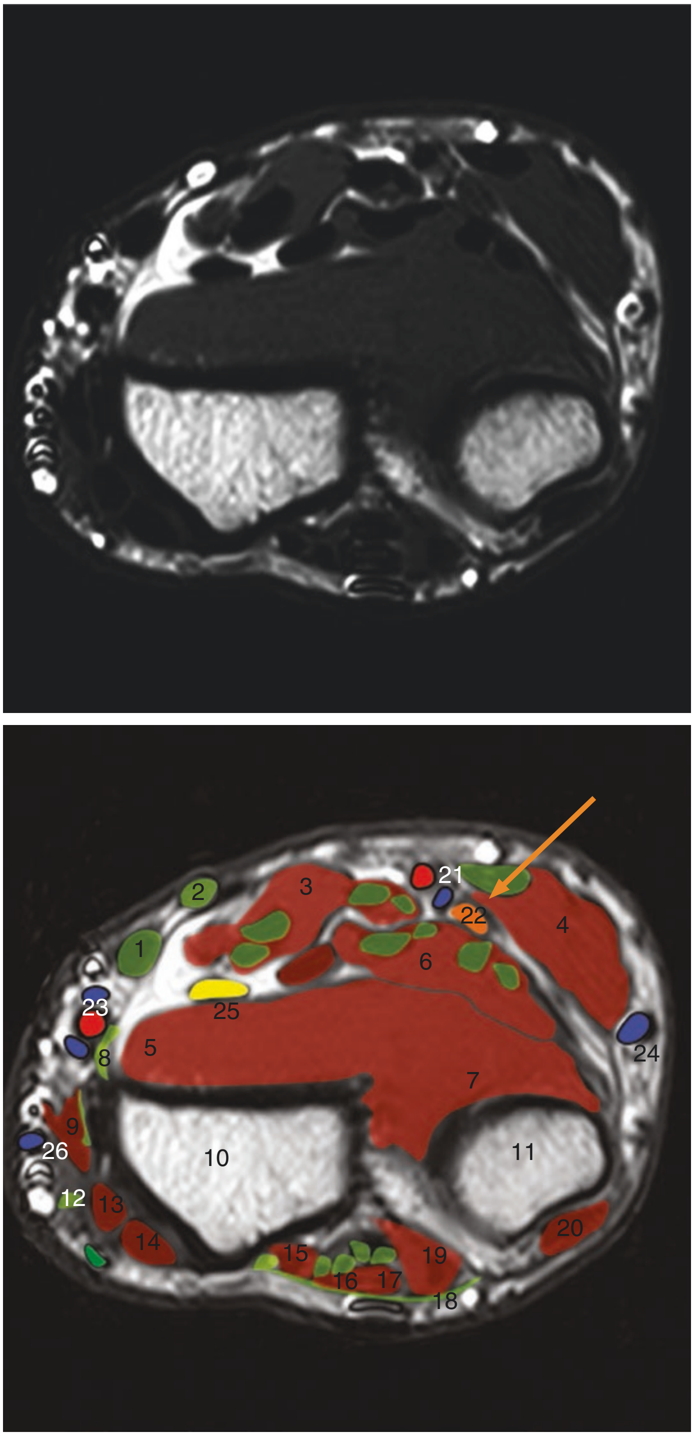
16- Ulnar artery and vein

17- Basilic vein

18- Anterior interosseous artery, vein and nerve

Figure U18. MRI scans in the forearm through the ulnar nerve.





1- Flexor carpi radialis muscle
2- Palmaris longus muscle
3- Flexor digitorum superficialis muscle
4- Flexor carpi ulnaris muscle
5- Flexor pollicis longus muscle
6- Flexor digitorum profundus muscle
7- Pronator quadratus muscle
8- Brachioradialis muscle
9- Abductor pollicis longus muscle
10- Radius
11- Ulna
12- Extensor pollicis brevis muscle
13- Extensor carpi radialis longus muscle
14- Extensor carpi radialis brevis muscle
15- Extensor pollicis longus muscle
16- Extensor digitorum muscle
17- Extensor digiti minimi muscle
18- Extensor retinaculum
19- Extensor indicis muscle
20- Extensor carpi muscle
21- Ulnar artery and vein
22- Ulnar nerve
23- Radial artery and vein
24- Basilic vein
25- Median nerve
26- Cephalic vein

Figure U19. MRI scans in the wrist through the ulnar nerve.

Pathology

Cubital Tunnel Syndrome

In the elbow, the ulnar nerve is situated behind the medial epicondyle of the humerus. It is accompanied by the superior collateral ulnar artery. It then goes in between the two heads of the flexor carpi ulnaris muscle. It can be compressed at this level (Figure U20).

Aetiology

- Compression: it is truly an entrapment neuropathy. The compression occurs at the level of the arch of the flexor carpi ulnaris muscle. This compression is more likely to happen after remodelling of bone, for post-injury reasons or not. Any cause of shrinking of this "ulnar tunnel" can be responsible for this syndrome. It is often due to a repeated, prolonged or sometimes iatrogenic compression—surgery in genupectoral position and prolonged anaesthesia with the arm in a wrong position or use of crutches. Diabetes, smoking and arterial hypertension are risk factors, as well as hypothyroidism and intensive manual labour.
- Traction: the region described above is an important stretching area of the ulnar nerve during repeated flexion motions of the elbow. At this level, nerve injuries are more likely to happen in the case of "system" diseases such as diabetes, renal failure, hepatocellular failure and vitamin deficiency, which can all weaken the nerve.

Clinical Significance

- Sensitive signs: the sensitive signs generally concern the last two fingers of the hand. It can be pain of neuropathic type or mere paraesthesiae. The paraesthesiae or pain can increase during the night, especially when the elbow is in a flexion position.

  Paradoxically, the first sensibility mode affected is the proprioceptive function and secondarily the epicritic function.
- Motor signs: in the forearm, the ulnar nerve takes charge of the innervation of the flexor carpi ulnaris and partially the flexor digitorum profundus muscle. In the hand, it innervates the major part of the intrinsic muscles except for the abductor pollicis brevis, opponens pollicis and the first and second lumbricals. Its motor impairment is therefore manifesting itself by an impossibility of adduction of the little finger and of flexion and extension for all the other fingers except for the thumb. Flexion deficit is higher for the metacarpophalangeal joints when the interphalangeal joints are maintained in an extension position.

  Froment's sign and an amyotrophy of the first interosseous space will be found belatedly, very noticeable on the dorsal face of the hand.

Clinical Forms

The revealing sign can be an amyotrophy of the interossei muscles, which later extends towards the other muscles. It must compel one to seek for a distal compression of the nerve at the level of the hand.

The sensitive signs may not appear for a long time, and the pain can stay localized in the elbow. An impairment of the flexor digitorum muscles remains minimal or non-existent in most cases, considering their double innervations.

Explorations

- Bilateral and comparative radiographies of both the elbows: the goal is to look for a radiopaque exostosis, proof of the possible existence of an arcade of Struthers.

  The arcade of Struthers is a fibrous band stretched between an abnormal exostosis, called "supracondylar process", situated 3–5 cm above the medial epicondyle and the junction of the medial epicondyle with the trochlea. It exists in 1% of subjects. This is the other nerve compression site that must systematically be sought for.
- An electroneuromyography objectifies the ulnar nerve injury and eliminates an associated impairment or a differential diagnosis.

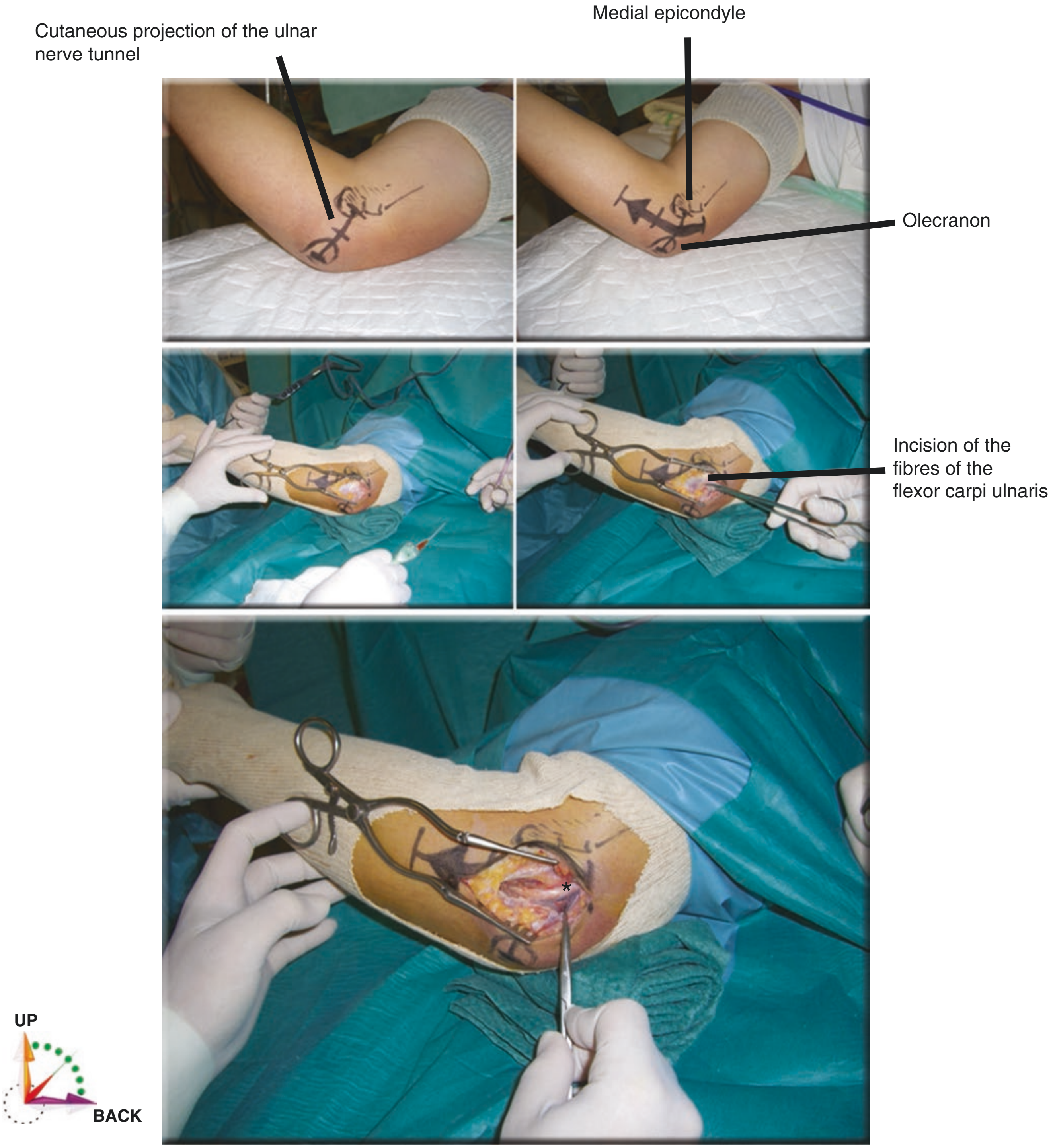

Cutaneous projection of the ulnar nerve tunnel
Medial epicondyle
Olecranon
Incision of the fibres of the flexor carpi ulnaris
*
UP
BACK

Figure U20. Pathology of the ulnar nerve: ulnar nerve entrapment at the elbow—decompression surgery in order to release the ulnar nerve (*) in its ulnar nerve tunnel.

Treatment

A change in the patient's habits in position, which goes towards avoiding the position with an elbow in flexion which is likely to compress the nerve, is recommended as first intention. An elbow orthosis for night use can be suggested.

If the medical treatment fails, a surgical opening of the arcade of the flexor carpi ulnaris is generally sufficient.

The surgery's result is good or excellent in 90–95% of cases.

The recovery period varies according to the severity of the disuse atrophy when surgery is performed and to whether the neuropathic character of pain is proven (Figure U21).

Ulnar Tunnel Syndrome (Guyon's Canal)

The ulnar canal is formed on the carpus by an expansion of the extensor retinaculum that inserts itself on the hamatum and pisiform bones (see above). The nerve can be compressed in this canal. At this position, the ulnar nerve splits into its two terminal branches (Figure U17).

Aetiology

- Compression: there was no reported case of a real entrapment neuropathy. There are two potential compression sites—either at the proximal level, at the level of the palmar carpal ligament or, more distally, under the arch formed by the pisiform and hamulus bones.

Clinical Signs

- Sensitive signs: the sensitive territory of the ulnar nerve includes the palmar face of the fifth finger and the medial half of the fourth finger. The symptoms associate pain, paraesthesiae, vasomotor disorders and epicritic and/or proprioceptive hypaesthesia of the ulnar region. They can be triggered by percussion of the nerve at this level (Tinel's sign). It is important to note that the ulnar nerve's territory has a variable size and that it can be spread out differently on the palmar face of the third, fourth and fifth fingers.
- Motor signs: the impairment is sensibly identical with the cubital tunnel syndrome. According to the level of compression, a disuse atrophy of the hypothenar and/or interossei muscles can appear. It is important to note that the flexor carpi ulnaris is spared by this motor impairment.

Clinical Forms

There are three possible clinical pictures depending on where the nerve injury is located:

- Type I injury, proximal, representing 30% of cases. It is mixed, sensitive and motor and is caused by synovial cyst or malunions in the wrist.
- Type II injury, representing 52% of cases. It affects the nerve after the latter gives off its sensitive branch. It is therefore a purely motor injury: the impairment is massive. It is referred to as type IIa injury if the compression affects the nerve before the origin of its hypothenar branches and therefore spares the hypothenar group. It is referred to as type IIb in cases of a more distal injury at the level of the hamulus. It is the most frequent form of injury. Type IIc injury is rarer, where the injury is outside and distally from the compartment, at the level of the arcade of the adductor digiti minimi, proximally related to the branches heading for the first dorsal interosseous muscle and the adductor pollicis.
- Type III injury, representing 18% of cases. It is purely sensitive because it affects this component at the end of the ulnar compartment in an isolated way. A motor impairment can also be seen when the palmaris brevis muscle is affected, causing a loss in the relief and of the palmar creases of the hypothenar eminence (Figure U22).

Explorations

- The level of compression can be identified using electrophysiological monitoring.
- The indication of an MRI must be discussed if there is any doubt of a synovial or fatty pathology or any other type of intrinsic/extrinsic compression of the nerve.
- Wrist radiographies are recommended. They allow investigation for the possibility of an abnormal osseous swelling.

Treatment

The treatment varies directly according to the cause. There is no general agreement. In the case of an acute or evolving extrinsic compression, a decompression surgery is often recommended.

Post-operative results are generally satisfying after a few months of follow-up.

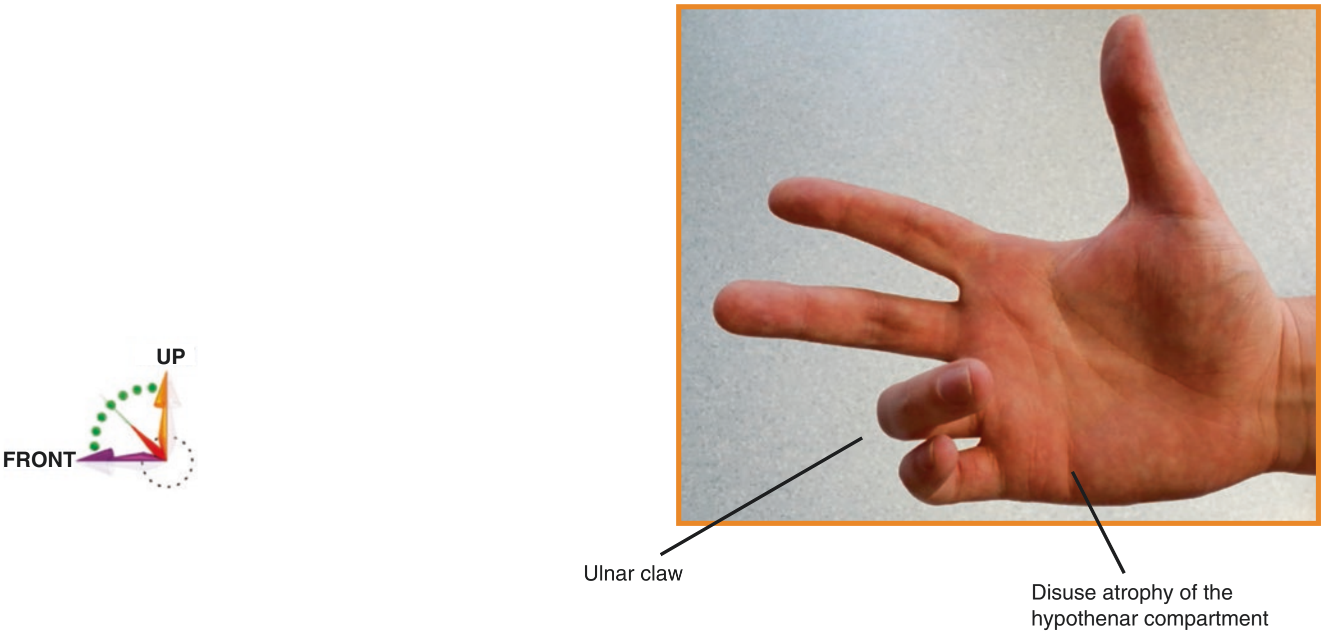

UP
FRONT
Ulnar claw
Disuse atrophy of the hypothenar compartment

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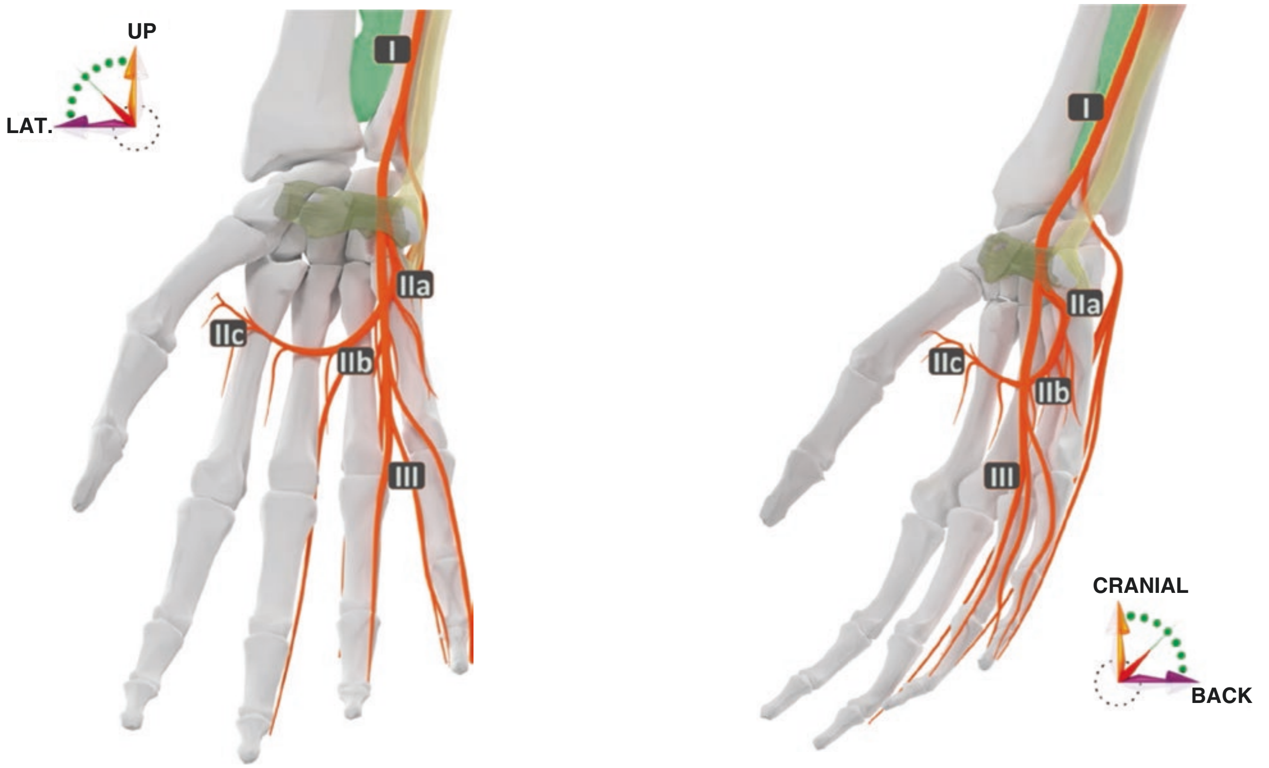
Figure U21. Ulnar nerve entrapment at the wrist—ulnar claw.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IIc
IIb
III
I
IIa
IIc
IIb
III
CRANIAL
BACK

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Figure U22. Anatomoclinical classification of ulnar nerve injuries. (1) Hamulus of hamate bone. (2) Deep motor branch of the ulnar nerve. (3) Pisiform bone. (4) Superficial sensitive branch of the ulnar nerve.

Morphological Data: Sono Anatomy

The ulnar nerve is a mixed nerve that originates in C8-T1 and constitutes one of the terminal branches of the medial bundle of the brachial plexus.

At the deep axillary level, it is located at the medial surface of the artery; at the mid-humeral level, it perforates the intermuscular septum separating the anterior brachial compartment from the posterior brachial compartment. The patient then finds himself in contact with the medial chief of the triceps brachii muscle, behind. At the posteromedial surface of the elbow, the nerve travels superficially through the medial epitrochlear-olecranon groove, passing into the forearm between the two heads of the flexor carpi ulnaris muscle; then it travels along the medial and anterior surface of the flexor digitorum profundus muscle, as also on the posterior surface of the flexor digitorum superficialis muscle. It is joined at the half of the forearm by the ulnar artery laterally and descends to the wrist, where it punctures the retinaculum of the flexors outside the pisiform, accompanied by the ulnar artery in the ulnar canal (formerly the Guyon canal).

Installation

The patient is in supine position, the arm in 90° abduction, the hand in pronation.

Equipment and Location

- Type of probe: surface probe, linear from 5 to 13 MHz.
- Probe axis: para-sagittal.

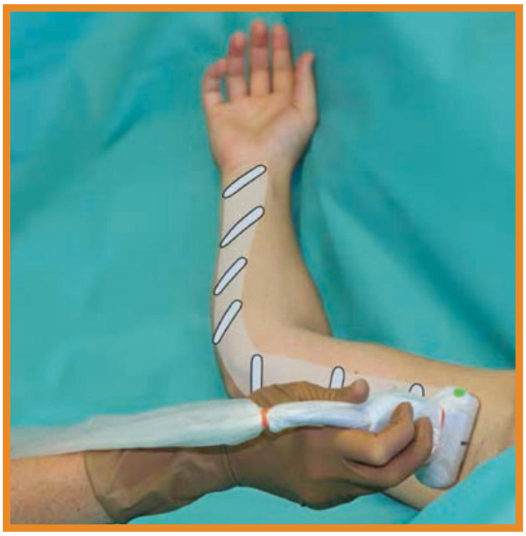
The skin marker is the top of the axillary cavity.

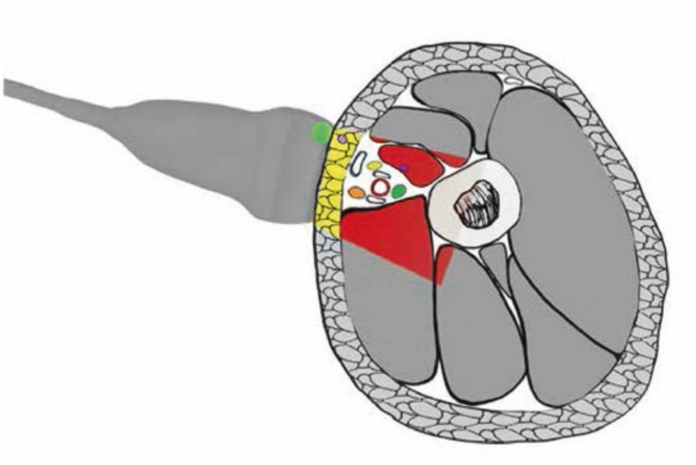
Ultrasound Procedure

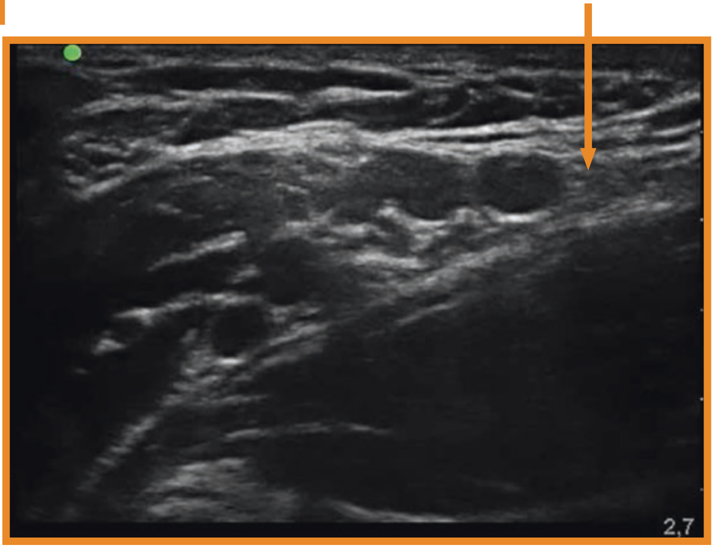
The structures to be identified are primarily vascular: artery and brachial vein, and also muscular: latissimus dorsi muscle. The latissimus dorsi muscle is observed later, i.e. in depth, and the biceps brachii muscle in front.

Compared to the brachial artery, which is an easy anatomical landmark located just in front of this structure, we find the median nerve and, in front, the biceps brachii muscle. The ulnar nerve is more posterior than the brachial artery (Figure U23).

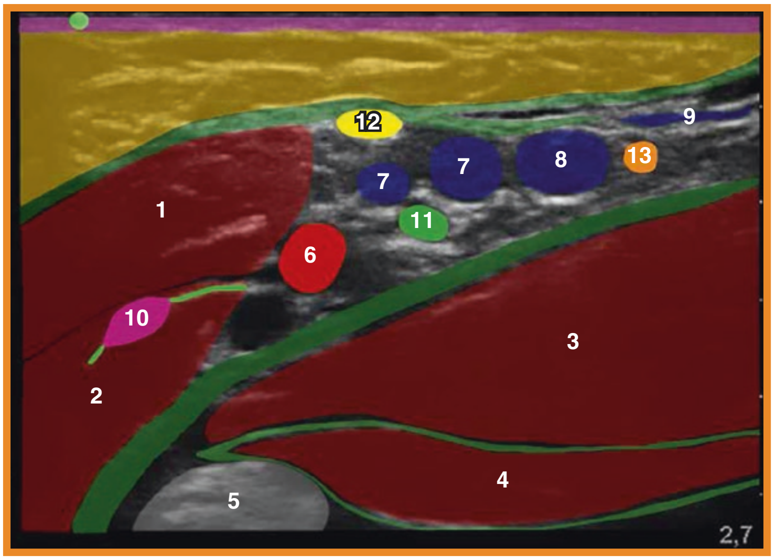
Synthesis: Compared to the brachial artery, the ulnar nerve is posterior, the median nerve is medial and the radial nerve is lateral.







1- Biceps brachii muscle
2- Coracobrachialis muscle
3- Latissimus dorsi muscle
4- Teres major muscle
5- Humerus
6- Brachialis artery
7- Brachialis veins
8- Cephalic vein
9- Basilic vein
10- Musculocutaneous nerve
11- Radial nerve
12- Median nerve
13- Ulnar nerve



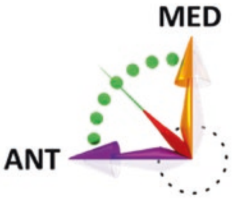
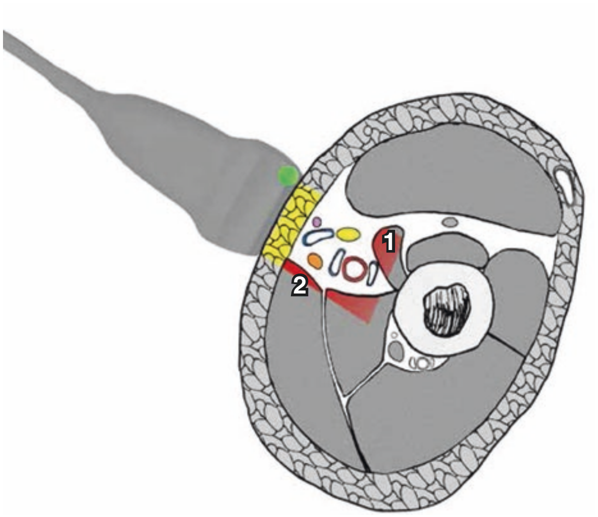


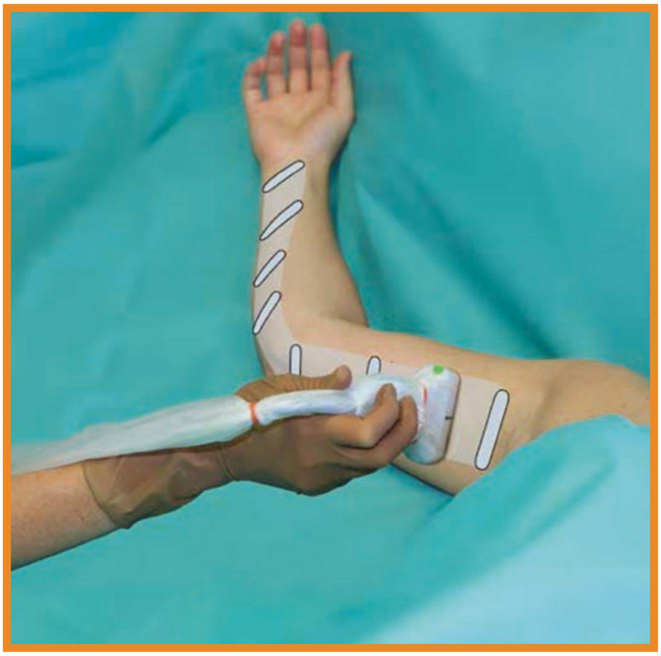
Figure U23. Ultrasound transversal views of the ulnar nerve at the distal third of the axillary pit.

At the level of the humeral canal, the nerve is in a posteromedial position with respect to the brachial artery; it is located just below the basilic vein. The medial cutaneous nerve of the forearm is the most medial. It should be noted that the basilic vein is not systematically found, although it is a prime reference point to identify median, cutaneous nerve of the forearm and ulnar nerves. In the absence of this vein, the brachial artery will be used, the three nerves being located more medially: median nerve in front, cutaneous nerve of the forearm being medial and the ulnar nerve posterior. At this level, it is sometimes difficult to identify, so it is important to track its path to the epitrochlear-olecranon groove, where it will be easily visible from the axillary cavity.

At the proximal part of the arm, the ulnar nerve remains a satellite of the artery and brachial vein.

It is interesting to identify the basilar vein by a compression-decompression movement of the ultrasound probe (Figures U24 and U25). This location makes it possible to avoid venipuncture during an anaesthetic procedure and to more easily identify the ulnar and median nerves.



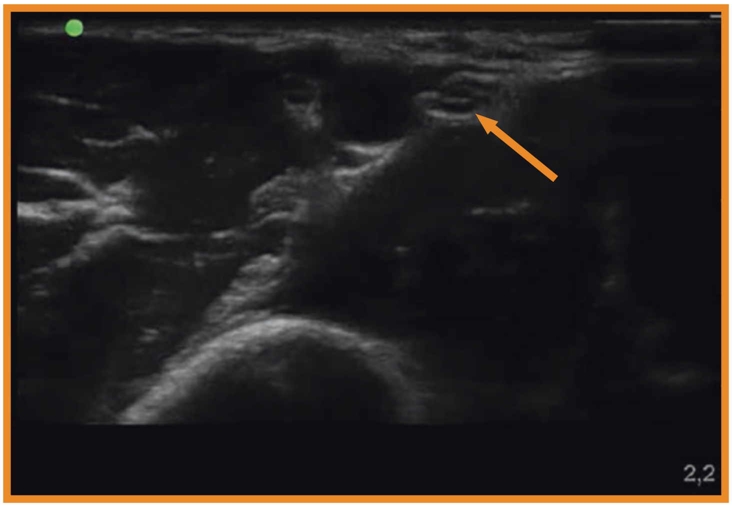


1- Coracobrachialis muscle

2- Medial and long heads of the triceps brachii muscle

3- Humerus

Figure U24. Ultrasound probe optimal positioning to visualize the ulnar nerve at the proximal third of the arm.



1- Coracobrachialis muscle

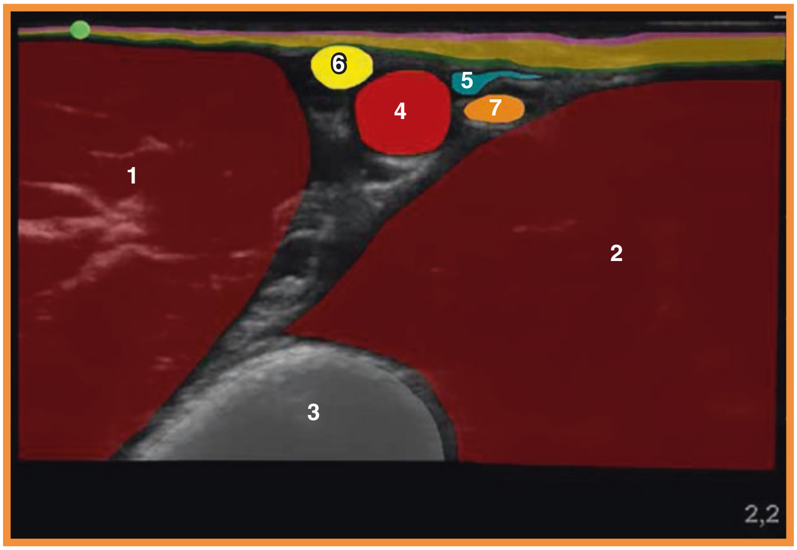
2- Medial and long heads of the triceps brachii muscle

3- Humerus

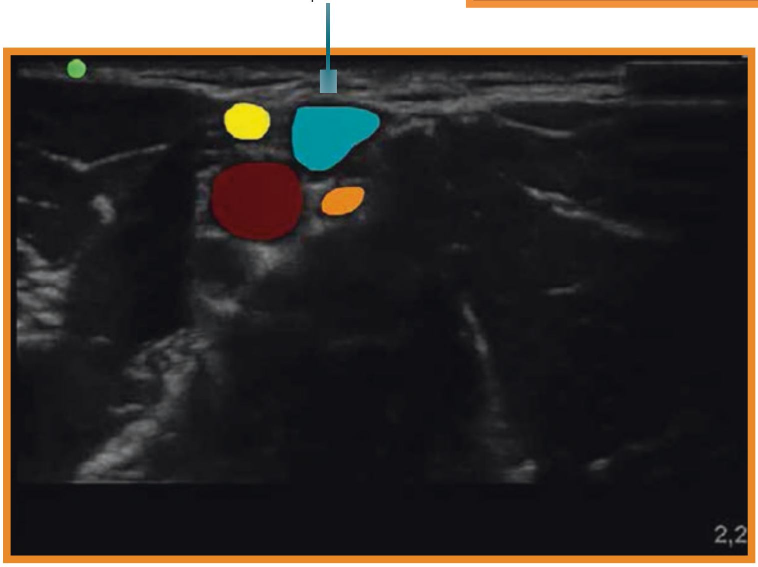
4- Brachialis artery

5- Basilic vein

6- Median nerve



Basilic vein without transducer compression



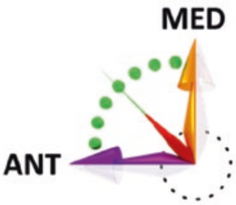


Figure U25. Ultrasound transversal views of the ulnar nerve at the proximal third of the arm.

At the middle part of the humerus, it perforates the intermuscular septum, passing from the anterior brachial chamber to the posterior brachial chamber, then it back in contact with the medial head of the triceps brachii muscle. It is separated from the brachial artery accompanied by the collateral ulnar artery (Figures U26, U27, U28, U29, U30, U31, U32 and U33).

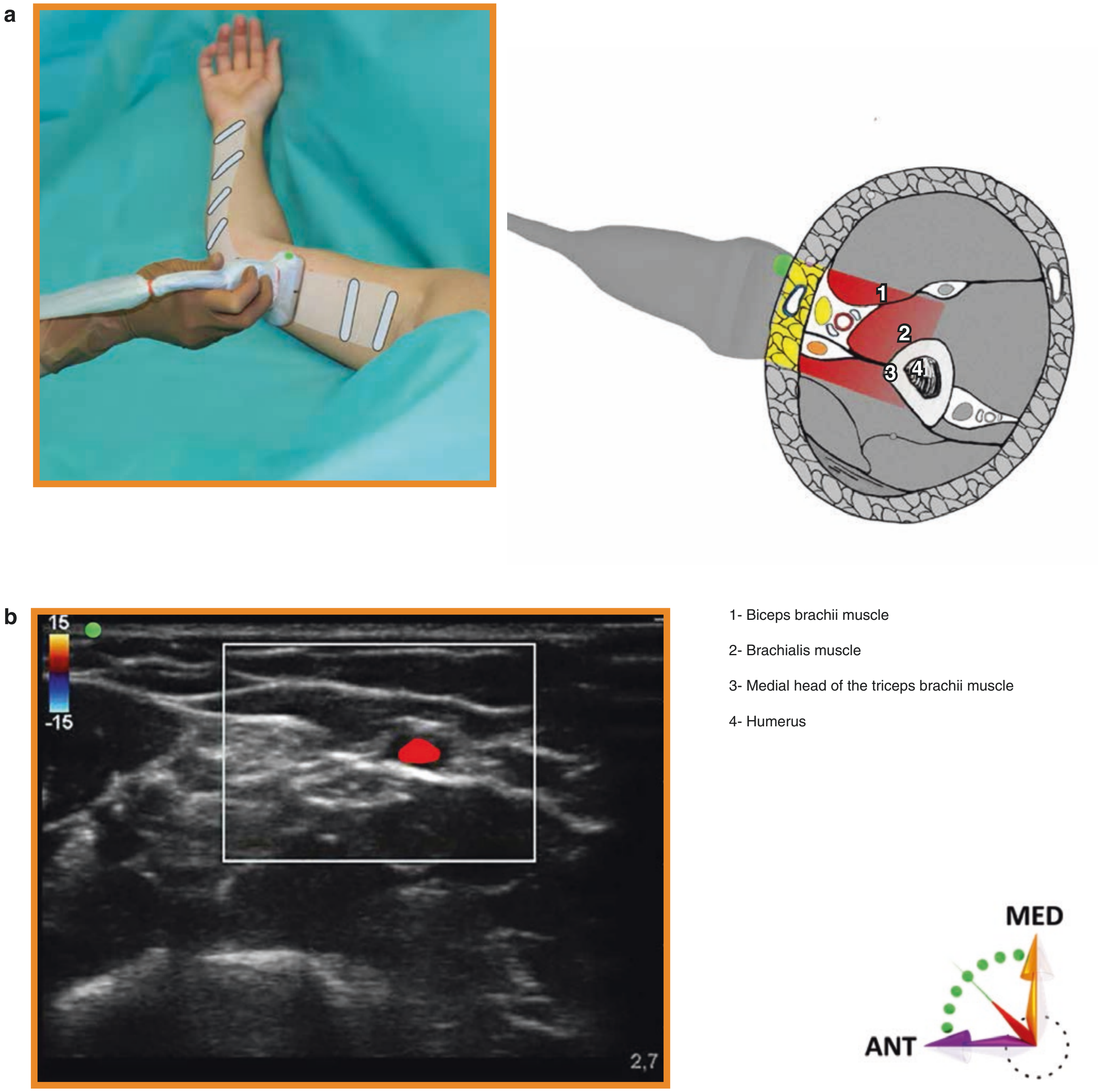
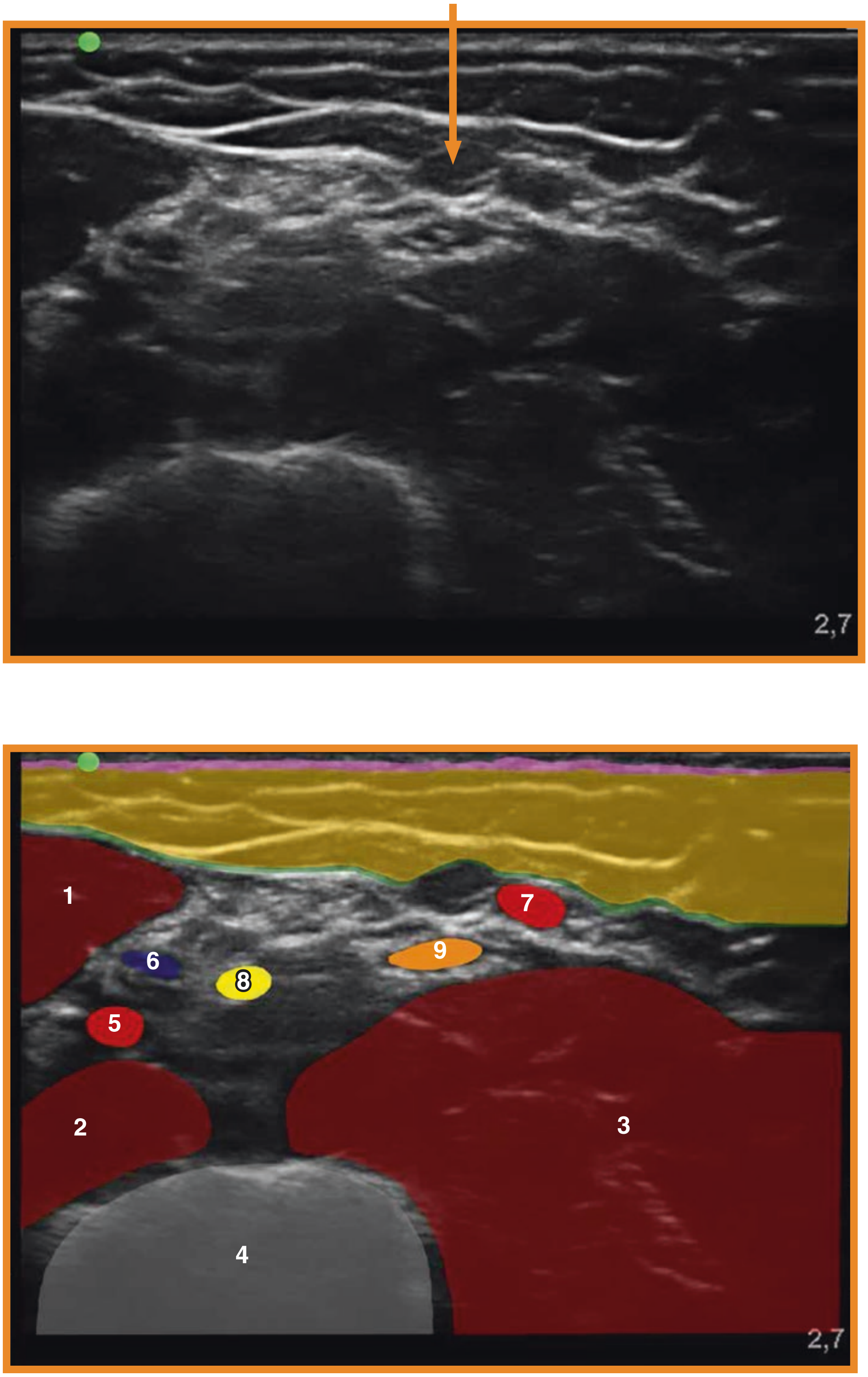

a
1
2
3
4
b
15
-15
2,7
1- Biceps brachii muscle
2- Brachialis muscle
3- Medial head of the triceps brachii muscle
4- Humerus
MED
ANT

Figure U26. (**a**) Ultrasound probe optimal positioning to visualize the ulnar nerve at the middle tier of the arm. (**b**) Doppler mode view.



1- Biceps brachii muscle

2- Brachialis muscle

3- Medial head of the triceps brachii muscle

4- Humerus

5- Brachialis artery

6- brachialis vein

7- Superior ulnar collateral artery

8- Median nerve

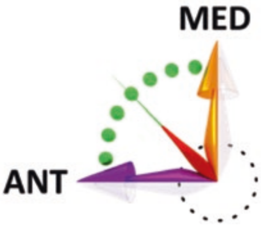


Figure U27. Ultrasound transversal views of the ulnar nerve at the middle tier of the arm.

On the posteromedial surface of the elbow, the nerve travels superficially through the medial epitrochlear-olecranon groove.

The patient's position may remain the same with the hand in supination and with the arm extended or the forearm bent at 90°, the hand rests on the chest, the ultrasound probe at the level of the medial epicondyle at the medial surface of the arm and the landmarks are mainly bony: the medial epicondyle with the trays.

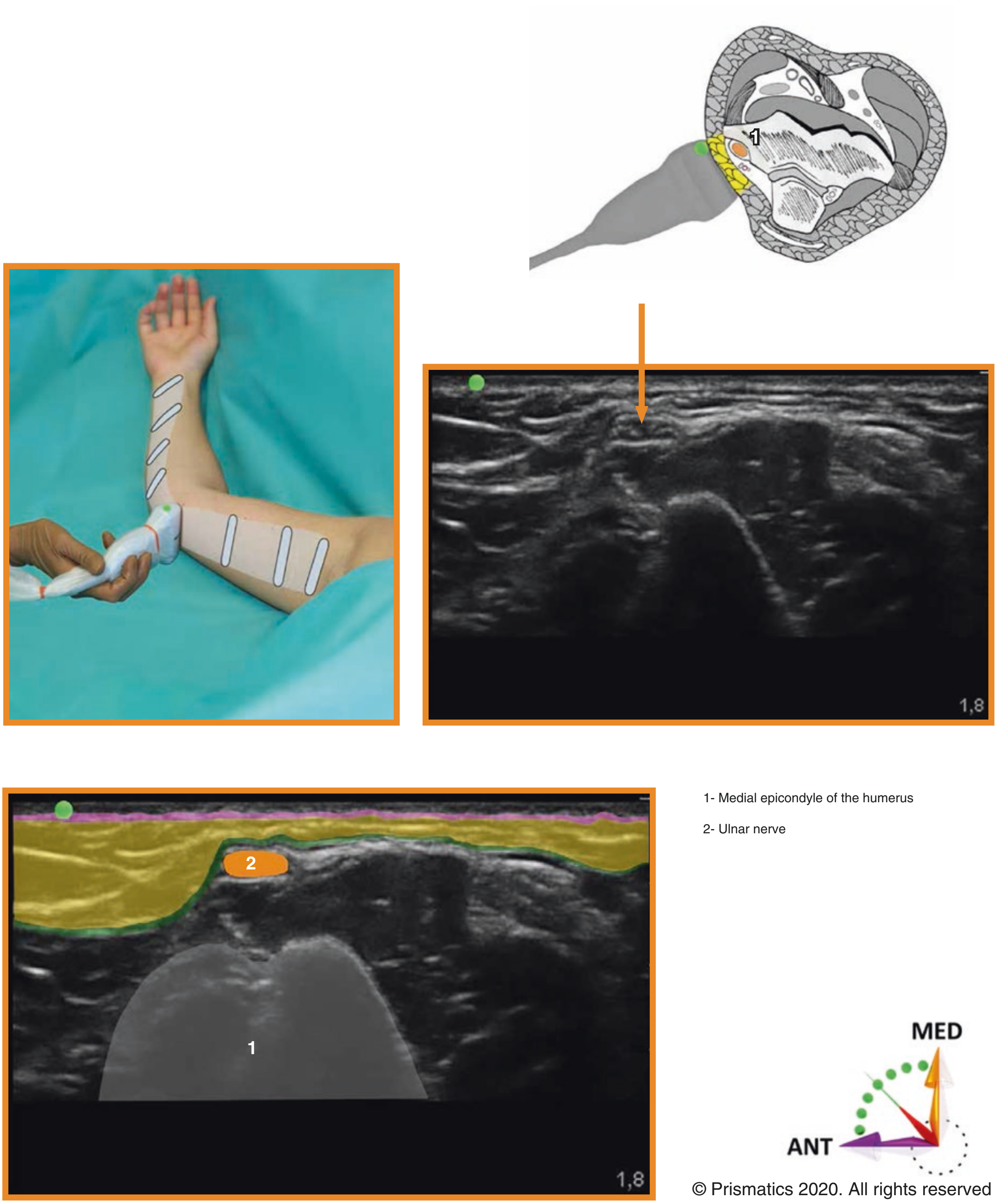


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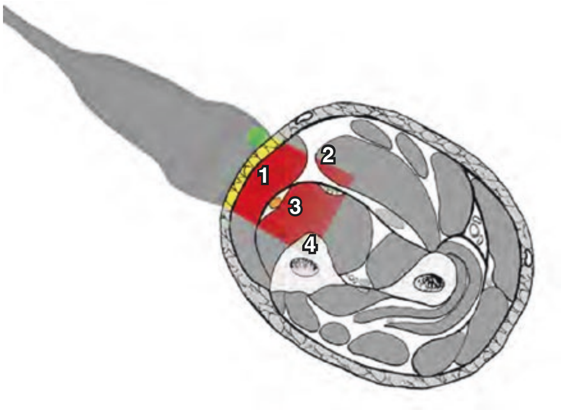
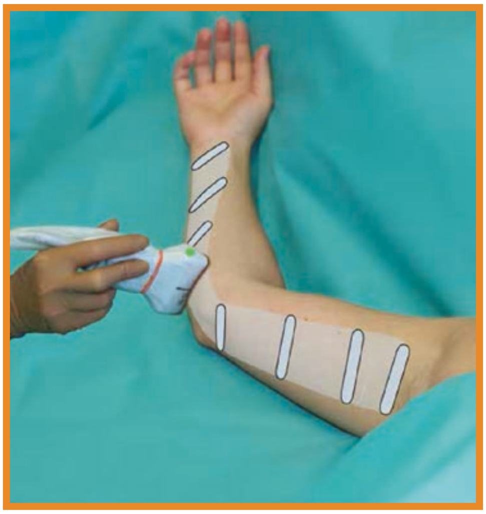
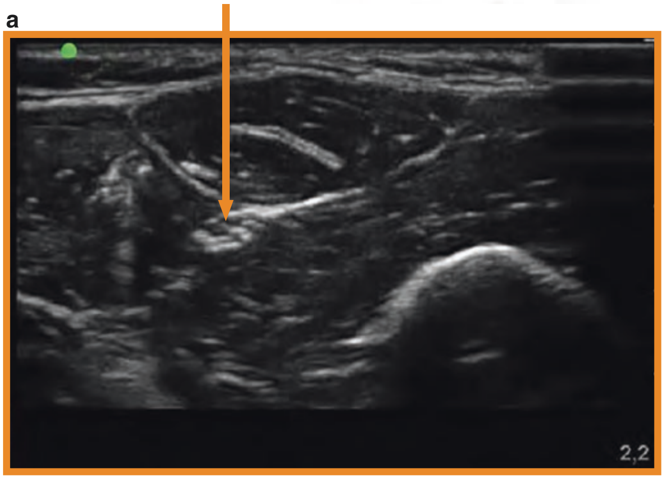
Figure U28. Ultrasound transversal views of the ulnar nerve at the distal third of the arm.

The ulnar nerve passes through the forearm between the two leaders of the flexor carpi ulnaris muscle. It travels on the medial and ventral side of the flexor digitorum profundus muscle and on the dorsal side of the flexor digitorum superficialis muscle.







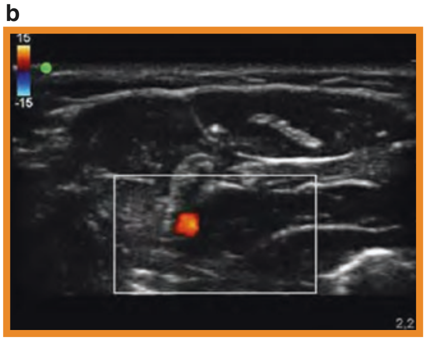
1- Flexor carpi ulnaris muscle

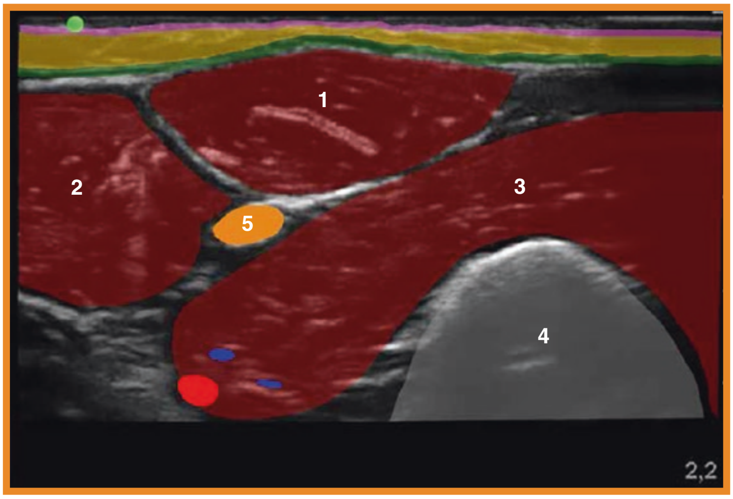
2- Flexor digitorum superficialis muscle

3- Flexor digitorum profundus muscle

4- Ulna

5- Ulnar nerve





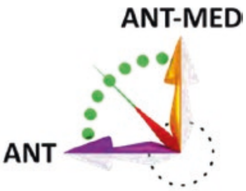
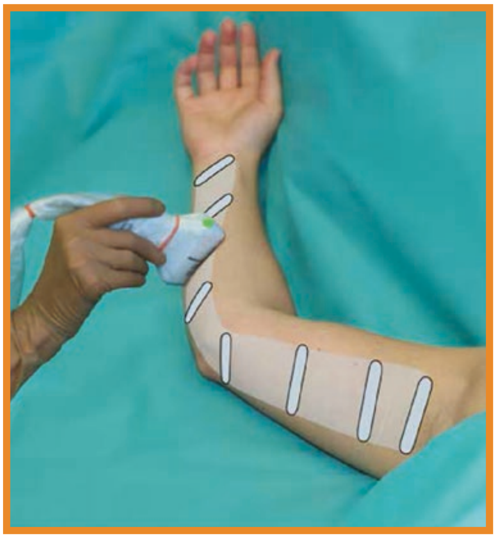


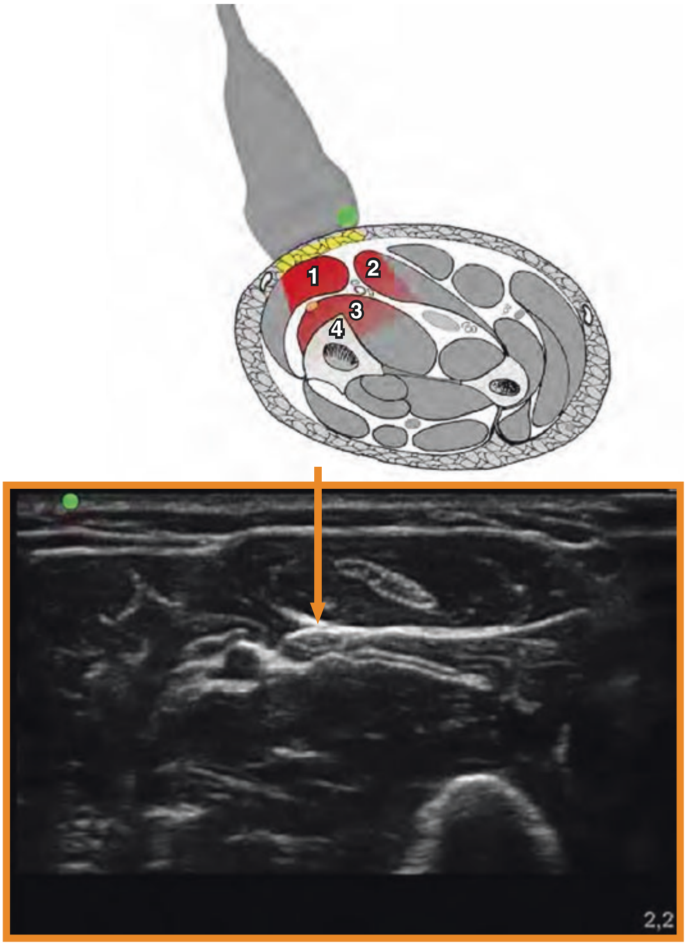
Figure U29. (**a**) Ultrasound transversal views of the ulnar nerve at the forearm proximal third. (**b**) Doppler mode view.

The Ulnar Nerve

The ulnar nerve is joined at the halfway point of the forearm by the ulnar artery, where it is median.

It is covered by the flexor carpi ulnaris muscle and then medially releases in relation to the tendon of this muscle.





1- Flexor carpi ulnaris muscle

2- Flexor digitorum superficialis muscle

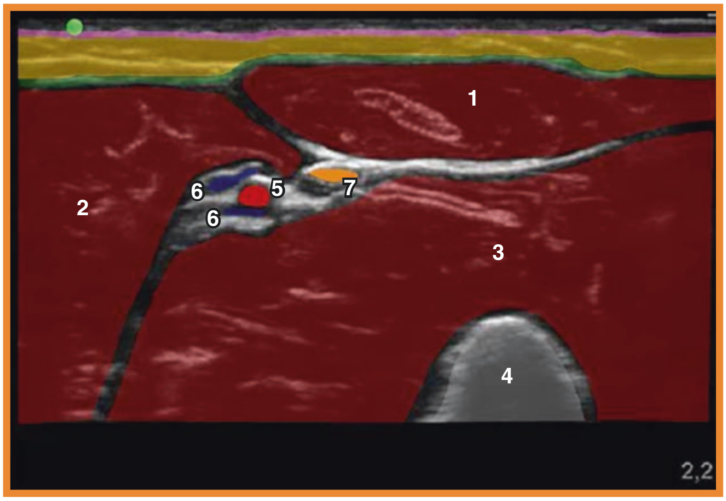
3- Flexor digitorum profundus muscle

4- Ulna

5- Ulnar artery

6- Ulnar veins

7- Ulnar nerve



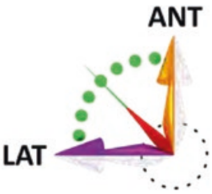
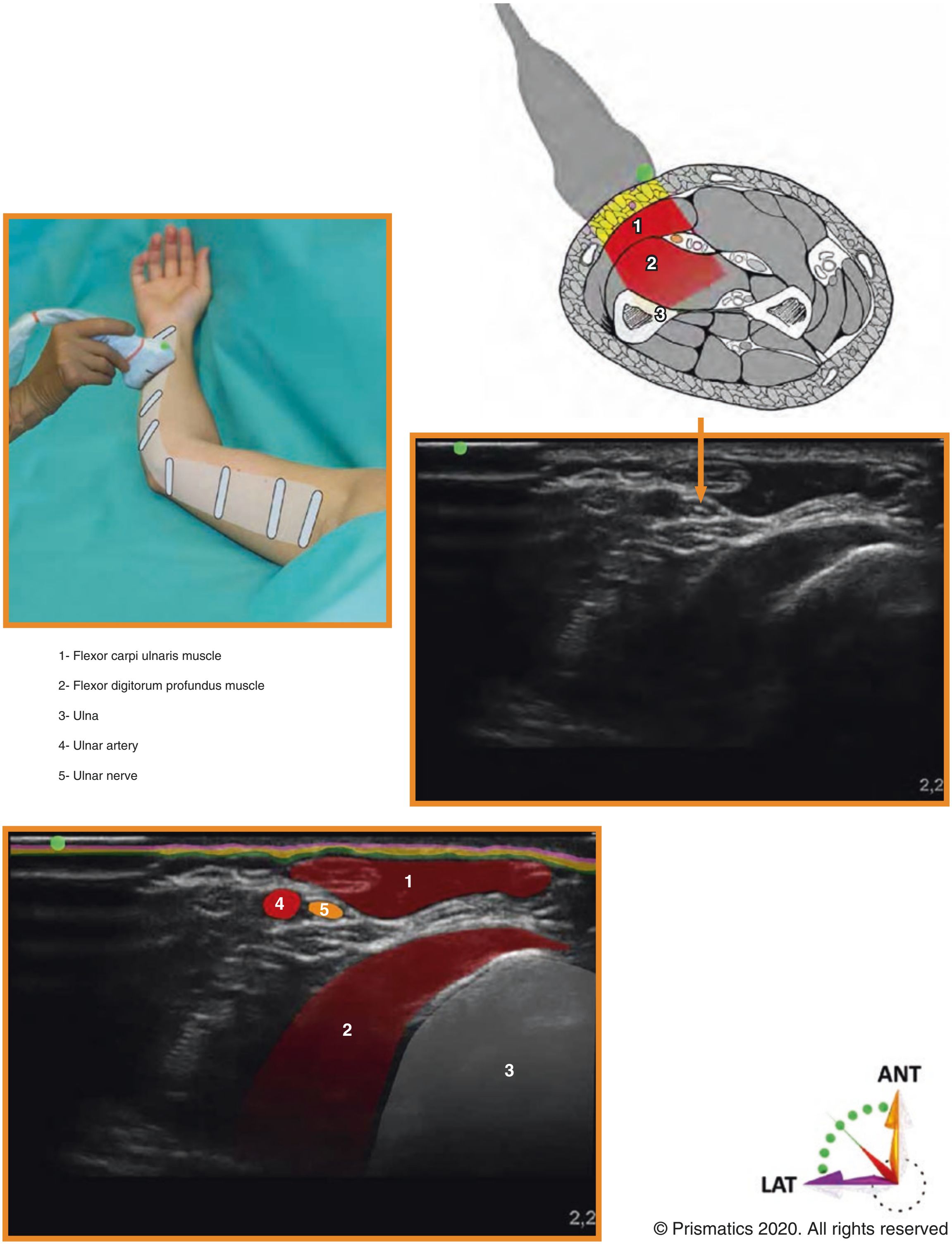


Figure U30. Ultrasound transversal views of the ulnar nerve at the forearm middle tier.

The ulnar nerve descends to the wrist where it perforates the retinaculum of the flexors laterally to the pisiform, accompanied by the ulnar artery in the ulnar canal.

At the exit of this ulnar canal, i.e. at the height of the pisiform bone, the ulnar nerve is divided into two terminal branches that are motor branches alone.

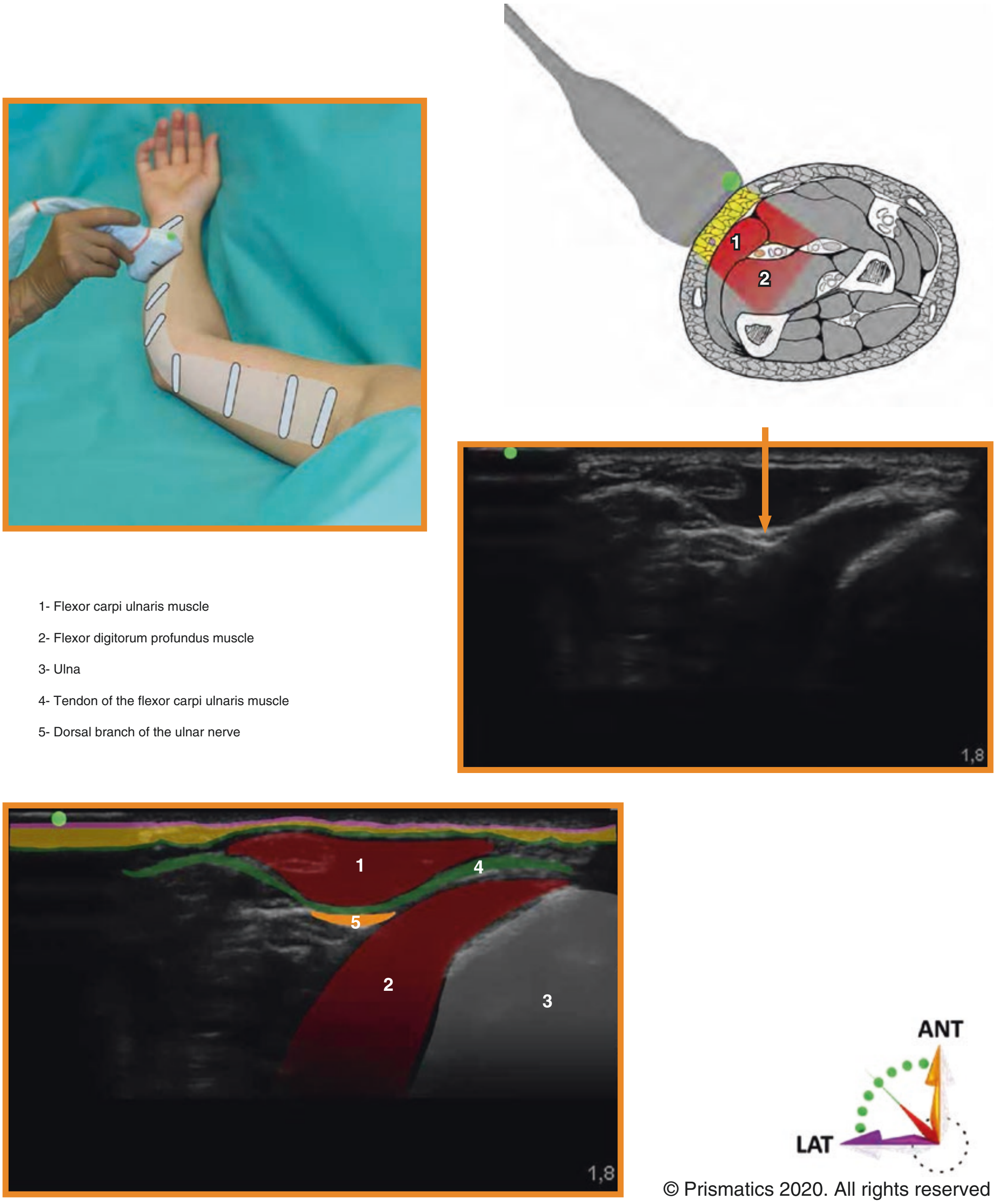


1- Flexor carpi ulnaris muscle
2- Flexor digitorum profundus muscle
3- Ulna
4- Ulnar artery
5- Ulnar nerve

Figure U31. Ultrasound transversal views of the ulnar nerve at the forearm distal third.

The dorsal branch of the ulnar nerve, a sensitive branch, is detached in the lower third of the forearm by passing under the tendon of the flexor carpi ulnaris muscle.

On the wrist, the probe is installed in a slightly medial axial position, on the front face of the wrist. The landmarks are the pisiform bone and the ulnar artery. In the ulnar canal, the



1- Flexor carpi ulnaris muscle
2- Flexor digitorum profundus muscle
3- Ulna
4- Tendon of the flexor carpi ulnaris muscle
5- Dorsal branch of the ulnar nerve

Figure U32. Ultrasound transversal views of the ulnar nerve dorsal branch, at the forearm distal third.

nerve is medial to the artery of which it is a satellite; more medially, we observe the flexor carpi ulnaris muscle. Depending on the position of the probe, in a proximal position to the pisiform, the ulna later will be observed.

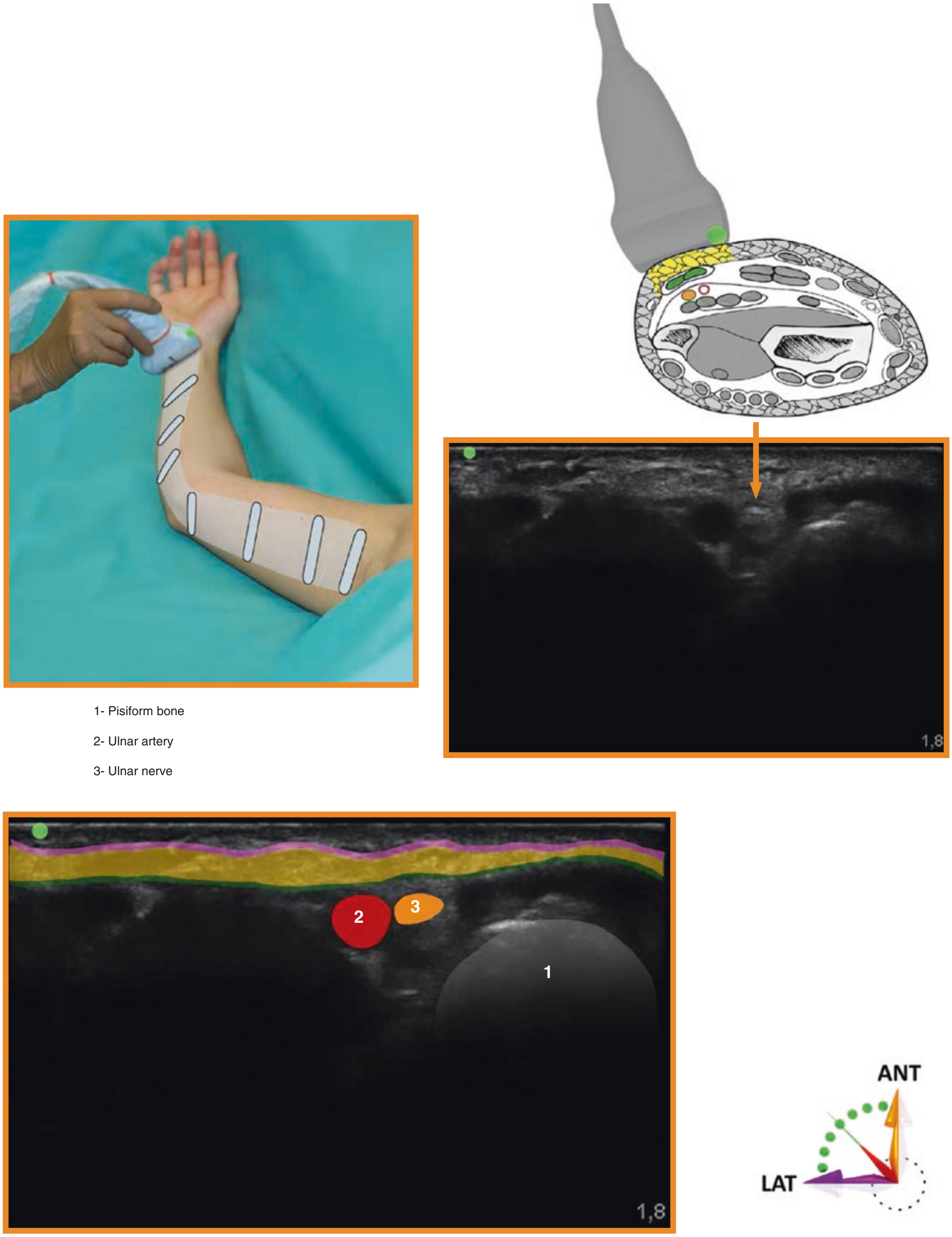

1- Pisiform bone
2- Ulnar artery
3- Ulnar nerve
1,8
1
2
3
1,8
ANT
LAT

Figure U33. Ultrasound transversal views of the ulnar nerve at the ulnar canal level.

Interventional Procedure

It always seems interesting to follow a nerve path during the disentanglement examination, in search of focal thickening of the nerve or a triggering cause. As for median nerve neuropathies, depending on the painful and/or deficient symptomatology, the existence or not of a deficit and its level will be investigated.

It must be kept in mind that a distal peripheral involvement of the ulnar nerve, at its exit from the ulnar canal, can only be motor without any sensitive abnormality.

Infiltration is possible at the elbow or at the outlet of the ulnar canal under ultrasound. The probe will be positioned as before. The nerve will be centred in the middle of the screen and visualized very superficially. The ultrasound injection will be performed outside the ultrasound field with real-time visualization of the entire injection, in order to avoid nervous and/or vascular trauma.

Anaesthetic Block of the Ulnar Nerve in the Elbow (Figure U34a)

This infiltration will most often be carried out using the out of plane technique because the position of the probe leaves very little room for manoeuvre between the skin and the bone for an in-plane technique.

The arm is positioned in elevation with a bending of the elbow at 120°, the hand resting on the contralateral shoulder and discrete adduction of the arm.

The ultrasound probe is placed in such a way that the ulnar nerve is in the centre of the screen throughout the procedure.

Infiltration will be performed from the proximal to the distal arm.

This anaesthesiological block is very superficial and care must be constantly taken not to traumatize the nerve during injection, as it is extremely weakened by chronic compression.

- Also, we will inject a small volume of anaesthetic (usually one millimeter is sufficient), to achieve transcutaneous penetration with a relatively flat needle angle.
- Hydrolocalization will be imperative by checking during injection that there is no nerve swelling, absence of intraneural oedema or increase in the size of the spinal sheath with intra-neural dispersion of the fascicles.

Anaesthetic Block of the Ulnar Nerve in the Ulnar Canal (Figure U34b)

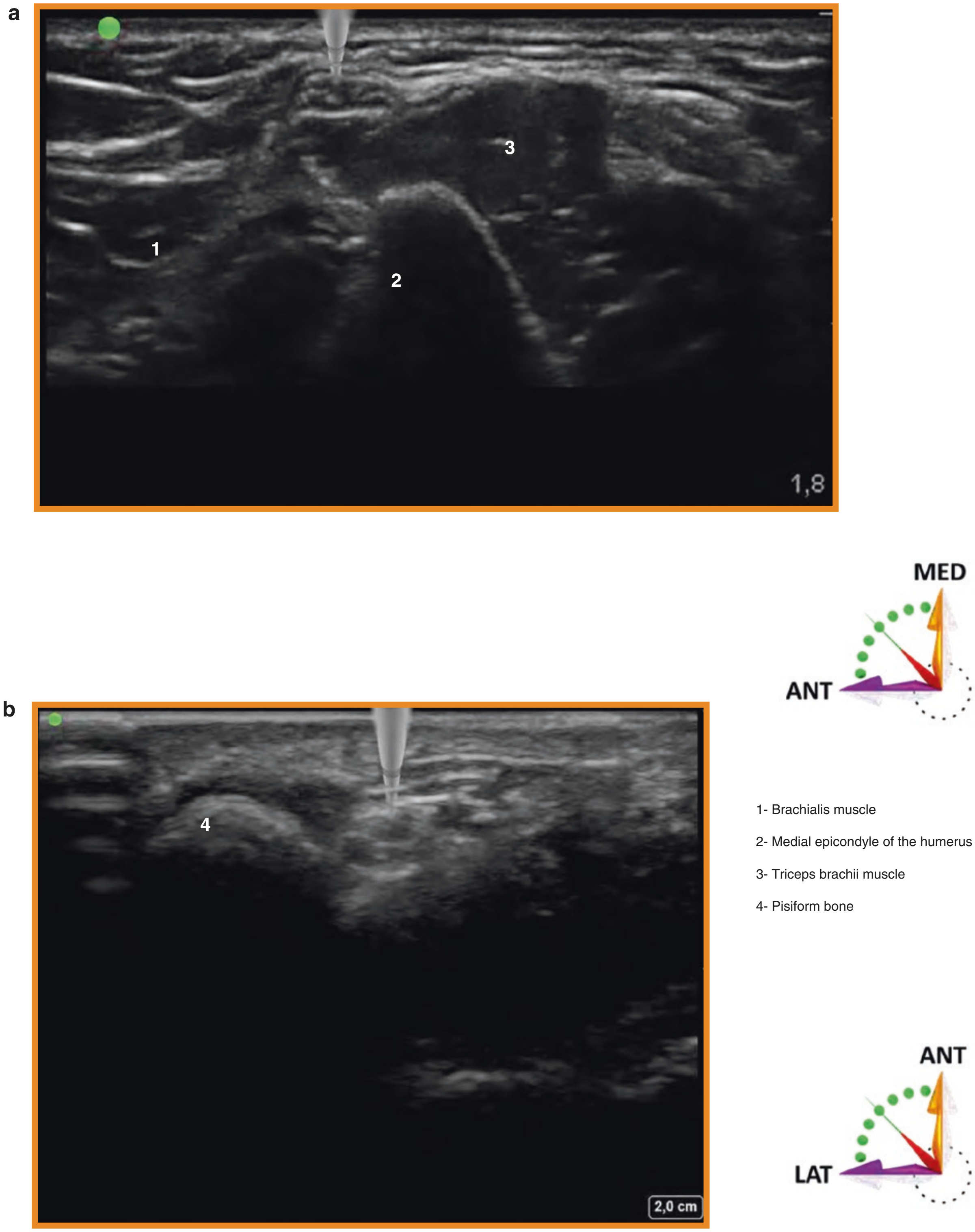
Here again, we prefer to carry out this infiltration using an out of plane technique.

The upper limb is positioned in abduction, palm in supination upwards.

The nerve will be positioned in the centre of the screen as usual with an injection that goes from the proximal to the distal part of the limb and a very flat angle, given its superficial nature.

The main danger of this test block is the ulnar artery attached to the nerve.

Hydrolocalization will be precious because if, at injection, there is no swelling of the vascular nerve sheath, a sting may be feared.



1- Brachialis muscle
2- Medial epicondyle of the humerus
3- Triceps brachii muscle
4- Pisiform bone

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Figure U34. Ultrasound probe optimal positioning to infiltrate the ulnar nerve (out of plane technique). (**a**) At the elbow level. (**b**) At the ulnar canal level (Ultrasound probe/13-6 with a 25 mm width).

Ulnar Nerve PNS

Concerning the implantation of a percutaneous nerve stimulation electrode, there are only few indications will be given the implantation difficulties. But there remains the possibility of a surgical approach to ensure surgical fixation, most often in the humeral canal.

Note that for ulnar topography pain, it is possible to directly stimulate the brachial plexus or the dorsal root ganglion, either in C7-C8 or C8-T1, to correspond in the truncated plane to the medial beam (Figure U35).

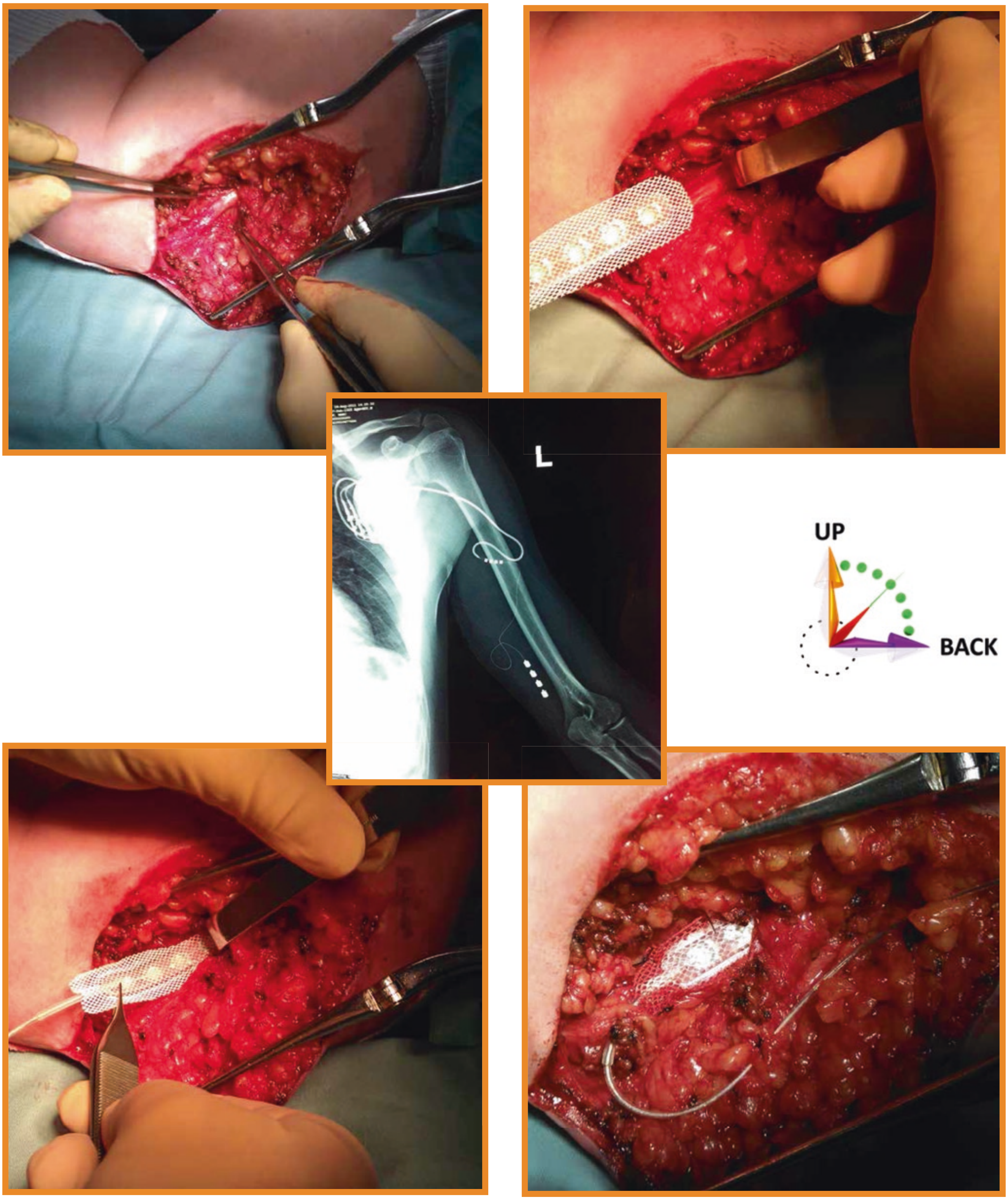


Figure U35. Ulnar nerve stimulation using a retrograde approach, just above the ulnar nerve gutter at the elbow level (in the middle: post-operative X-Ray).

Surgical Procedure

Surgical Approaches

On the Arm

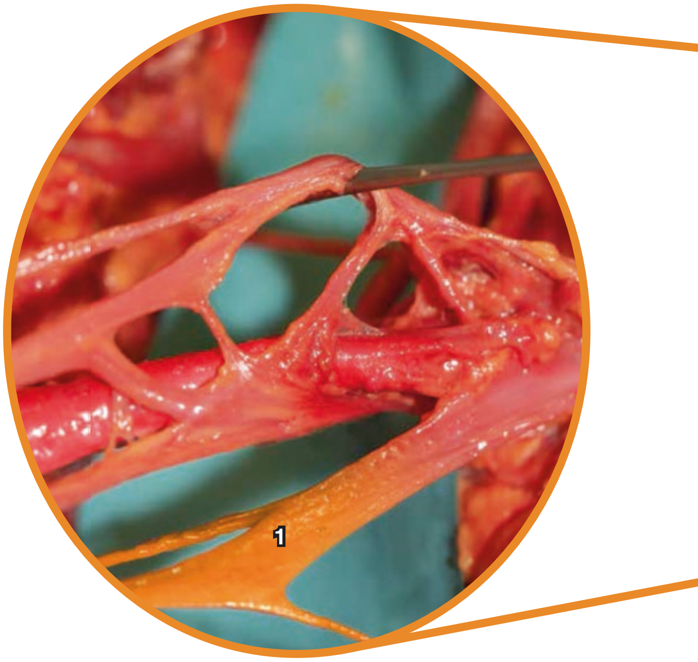
Skin Incision
The incision is made opposite the internal brachial canal and extends downward to the medial epicondyle. The ulnar nerve is located just behind the fascia.

At the elbow, installation is carried out by adduction and external rotation of the arm and identification of the incision at mid-distance between the olecranon and the medial epicondyle in order to expose the epitrochlear-olecranon groove facing each other (Figure U36).

Nervous Exposure
The ulnar nerve is located just behind the fascia. At the upper arm, it is located in front of the inner inter-muscular septum and behind the humeral artery and median nerve. At the middle part of the arm, it punctures the wall to press against its deep face in a groove of the triceps brachii muscle accompanied by the superior ulnar collateral artery. The ulnar nerve possesses no branch at the arm level, which greatly facilitates its mobilization.

At the Elbow

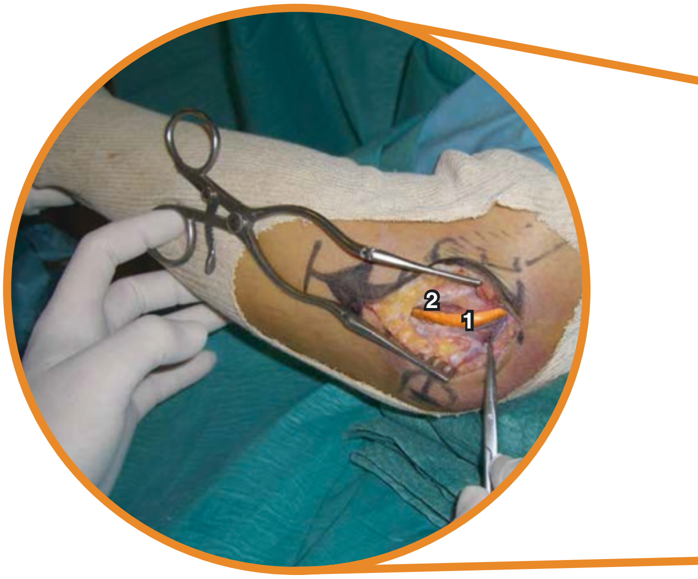
The internal intermuscular septum is identified at the upper part of the surgical field, behind which the ulnar nerve and its collateral artery are located. It can be followed in the epitrochlear-olecranon groove before it enters between the two leaders of the flexor carpi ulnaris muscle. Careful section of the fascia covering the gutter, once the nerve has lifted off its deep surface, allows it to be easily mobilized (Figure U36). When it is released, it is necessary to flex the forearm on the arm to ensure that it does not dislocate forward while the gutter is open.



1- Ulnar nerve

2- Flexor carpi ulnaris muscle

3- Long head of triceps brachii muscle



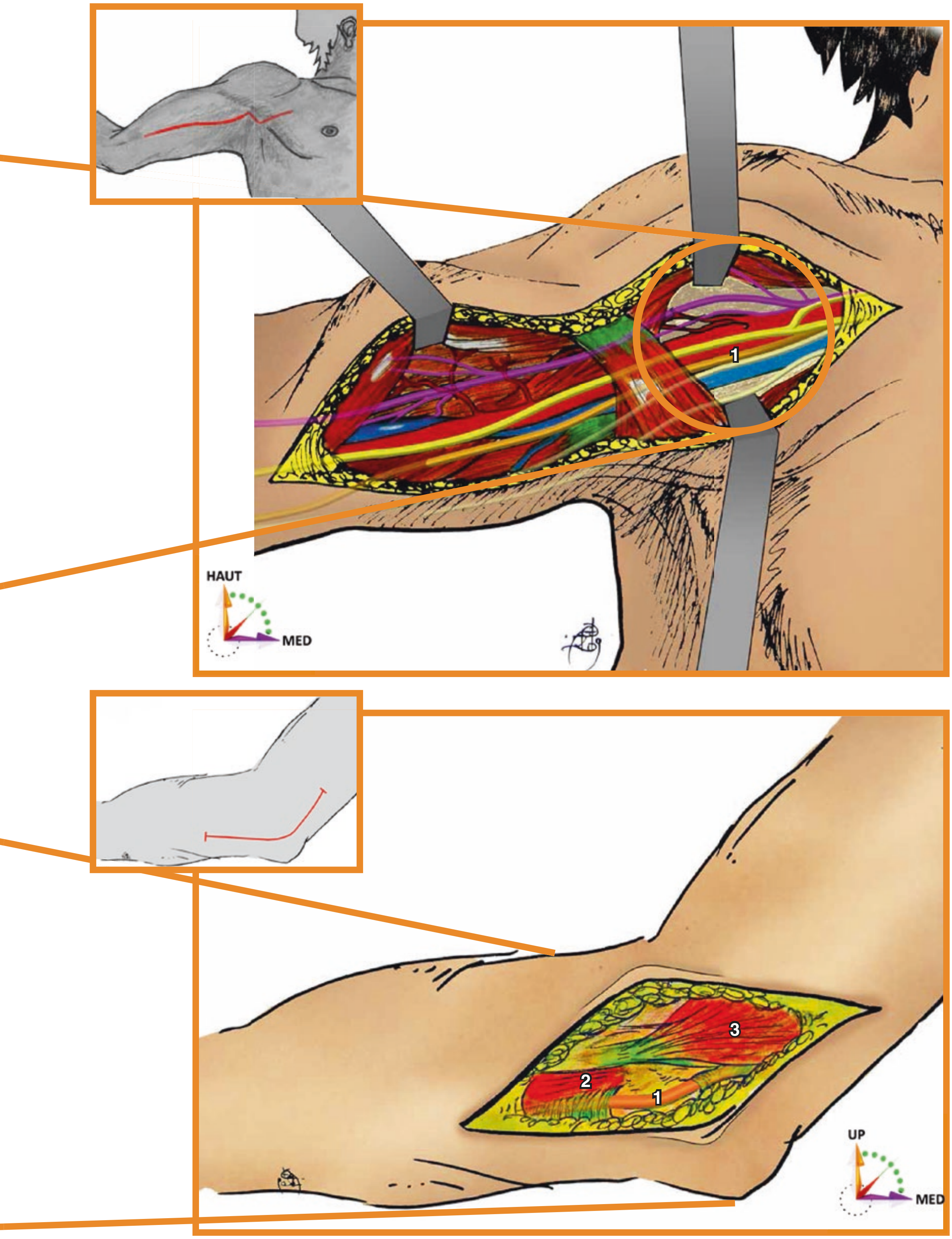

1
HAUT
MED
3
2
1
UP
MED

Figure U36. Surgical approach of the ulnar nerve at the arm and the elbow level.

At the Forearm

The incision follows the anterior edge of the flexor carpi ulnaris muscle. Its radial edge is released and cleaved from the flexor digitorum superficialis muscle and palmaris longus muscle to reveal in depth, the ulnar nerve and artery that travel to its outer edge (Figure U37).

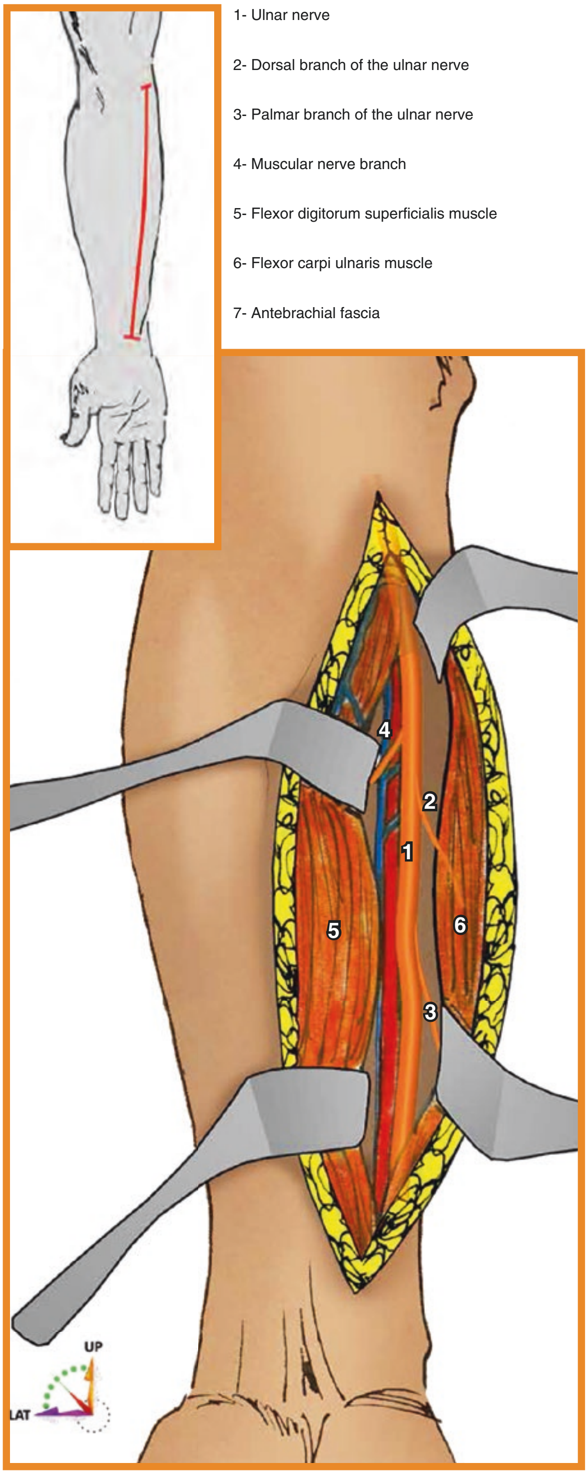
Distally, once the aponeuroses of the forearm and palm are severed in the axis, the ulnar nerve is located at the radial edge of the inwardly reflexed flexor carpi ulnaris tendon. The nerve is inside the artery (Figures U37 and U38). Its cutaneous dorsal branch is detached between 5 and 8 cm above the wrist fold and must be clearly identified.

At the wrist, the ulnar nerve enters the Guyon lodge through the deep face of the volar ligament, bathing in adipose tissue outside the pisiform.

The vascular-nervous bundle travels in the surface area with respect to the annular ligament of the carpus.

Technical Pitfalls

- Injury to the cutaneous dorsal ulnar branch
- Vascular lesion of the ulnar arterial axis at the forearm
- Chronic dislocation of the nerve at the elbow if the fascia sheathing it in the gutter is not restored by a few loose points before closing



1- Ulnar nerve
2- Dorsal branch of the ulnar nerve
3- Palmar branch of the ulnar nerve
4- Muscular nerve branch
5- Flexor digitorum superficialis muscle
6- Flexor carpi ulnaris muscle
7- Antebrachial fascia

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Figure U37. Surgical approach of the ulnar nerve at the forearm level.

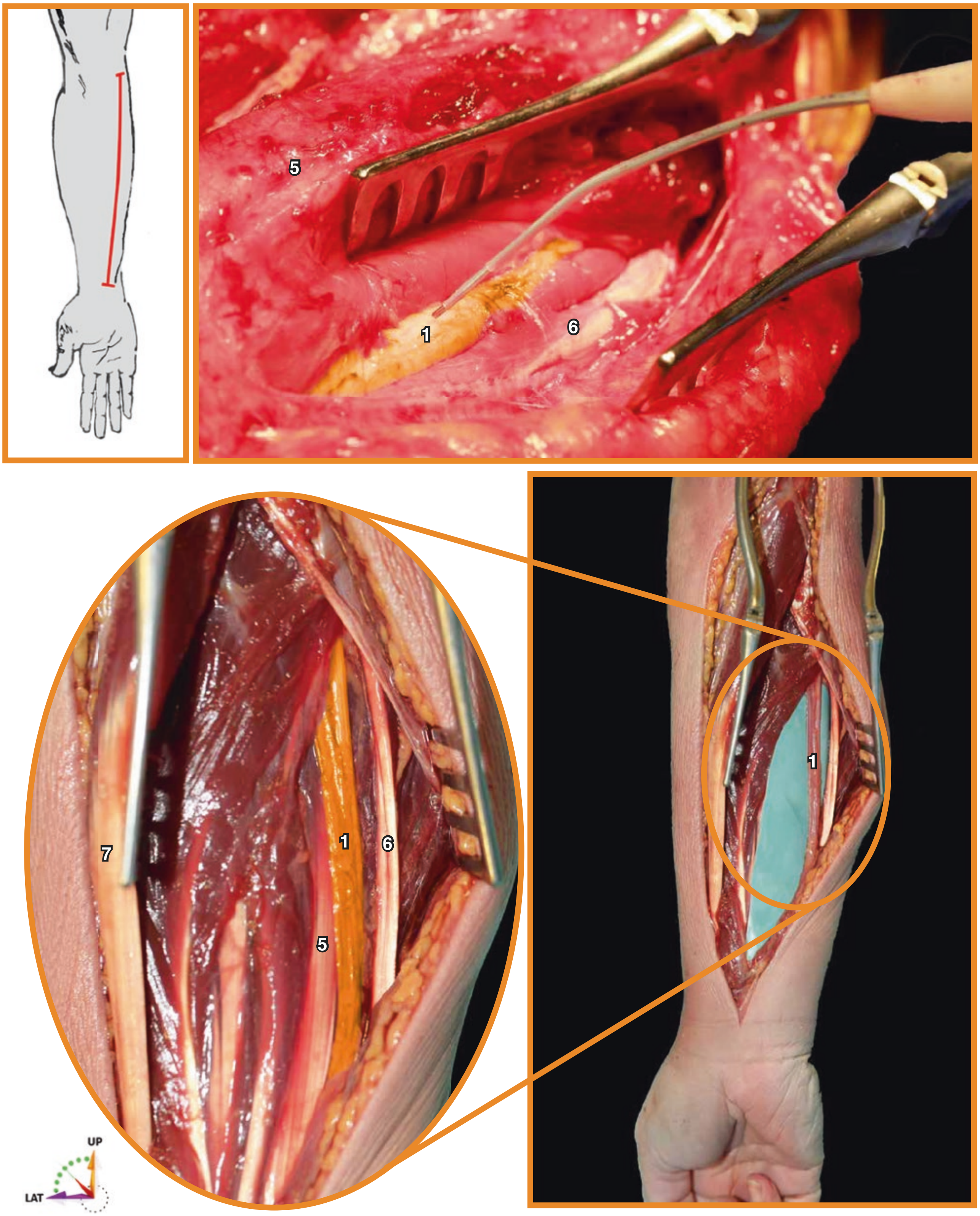
5
1
6
1
7
1
6
5
UP
LAT

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Figure U38. Surgical approach of the ulnar nerve at the forearm level.

By Hand

Skin Incision

The incision will follow the different access folds in a Z-shape to clear the interosseous trunk.

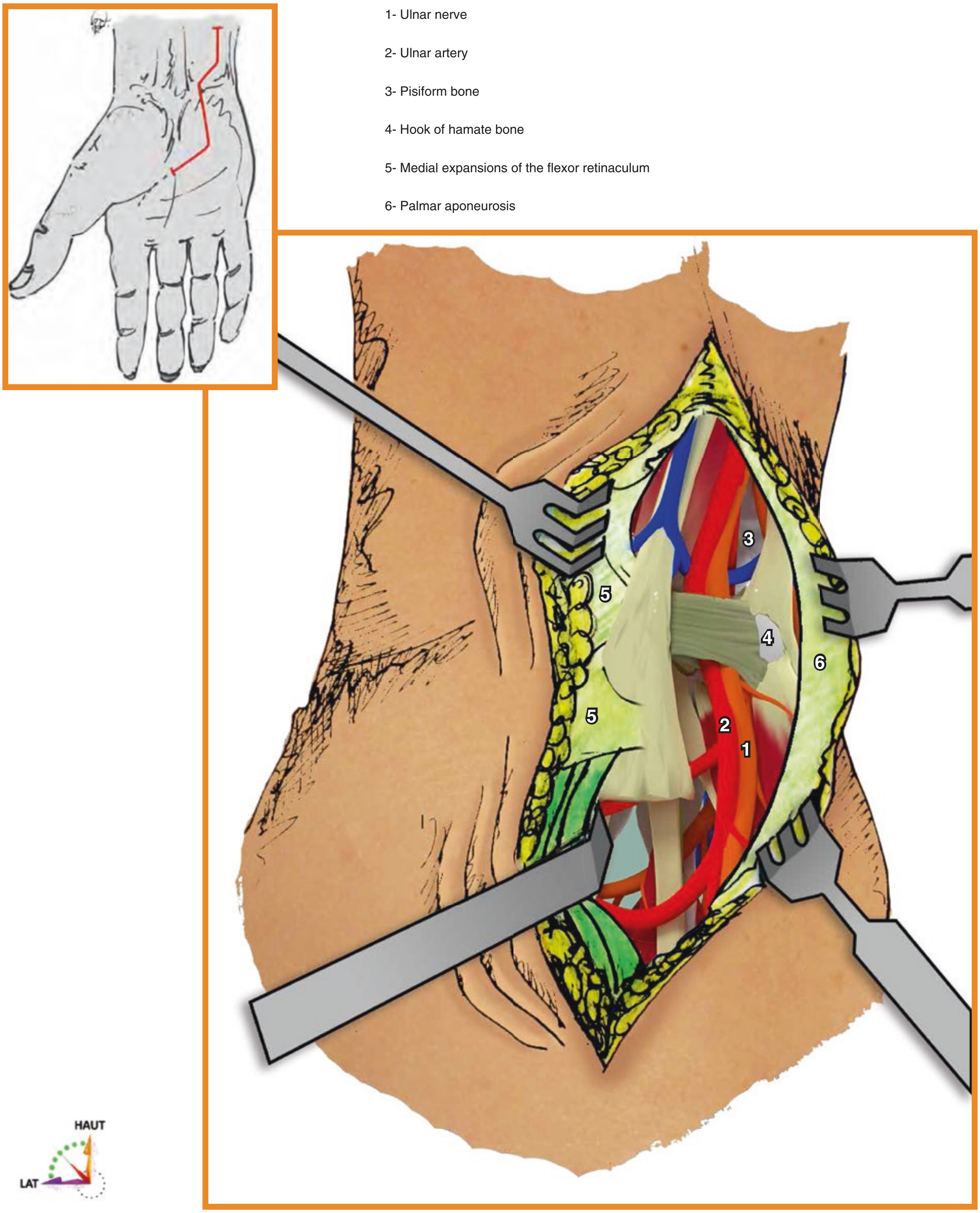
Nervous Exposure

In Guyon's lodge, the nerve is divided into a motor branch and a sensitive branch. The motor branch is on its ulnar edge and sinks like a slide between the flexor digiti minimi brevis and the abductor digiti minimi muscles to regain the depth of the palm.

The superficial branch innervates the long palmar muscle and is divided into two digital branches for sensitivity of the palmar surface of the last two fingers. The ulnar artery that accompanied the nerve outside, in the Guyon lodge, moves towards the radial part of the palm to form the superficial palmar arch, while the deep branch of the artery, accompanying the deep branch from the ulnar nerve to the palm, extends into the deep palmar arch (Figure U39).

Main Technical Trap

- Vascular lesion from the arterial arcade to the palm of the hand.



1- Ulnar nerve

2- Ulnar artery

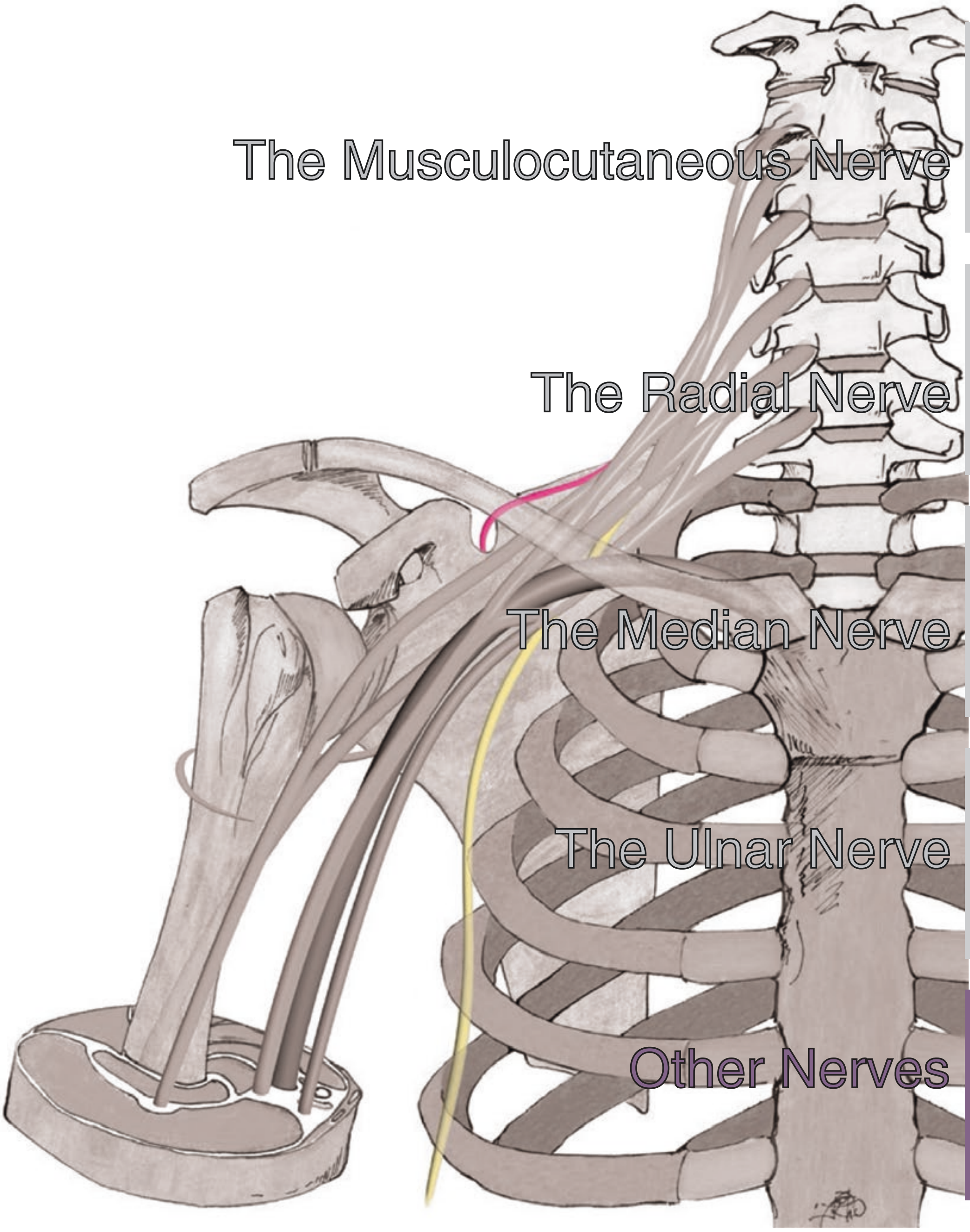
3- Pisiform bone

4- Hook of hamate bone

5- Medial expansions of the flexor retinaculum

6- Palmar aponeurosis

Figure U39. Surgical approach of the ulnar nerve at the hand level.



The Axillary Nerve

The Musculocutaneous Nerve

The Radial Nerve

The Median Nerve

The Ulnar Nerve

Other Nerves

SSc
LT

The Suprascapular Nerve

Morphological Data

The suprascapular nerve is a motor nerve. It is a collateral branch of the upper trunk of the brachial plexus and is responsible for the innervation of the scapular area.

Origin

It comes from the C5 to C6 roots, in the upper trunk of the brachial plexus. It originates where the brachial plexus splits into anterior and posterior division, at the level of the interscalene triangle (Figure SSc1).

Path

The suprascapular nerve path is deep, at the ventral face of the trapezius and omohyoid muscles. It then goes behind the clavicle under the insertion of the trapezius. It goes above the scapula through the suprascapular notch on the upper border of the scapula (Figure SSc2).

At this level, it faces the suprascapular artery and the transverse scapular ligament. The nerve may give rise to a branch that accompanies the artery above the transverse scapular ligament.

It then goes through the spinoglenoid notch under the transverse scapular ligament and around the lateral border of the spine of the scapula in order to penetrate the infraspinous fossa, which is where the nerve ends (Figure SSc3).

Neurovascular Relations

In the suprascapular notch, the suprascapular artery, the transverse scapular ligament and the suprascapular nerve can be found from top to bottom (Figure SSc2).

Collateral Branches

The suprascapular nerve successively gives off:
- Articular branches for the acromioclavicular and glenohumeral joint
- Cutaneous branches in 1/3 of individuals. These branches go through the suprascapular notch in front of the coracoacromial ligament and become subcutaneous when they perforate the deltoid muscle
- Muscular branches for the supraspinatus muscle

Terminal Branches

The suprascapular nerve ends at the level of the infraspinatus muscle when it distributes its motor fibres.

Motor Function

The suprascapular nerve takes charge of the innervation of the supraspinatus and infraspinatus muscles. The supraspinatus muscle is considered as the initiator of abduction movements and is in charge of elevating the head of the humerus at the beginning of abduction movements. The infraspinatus muscle allows movements of abduction and lateral rotation of the arm on the shoulder. Therefore, the suprascapular nerve takes charge of the elevation of the head of the humerus, the abduction and partially the lateral rotation of the arm.

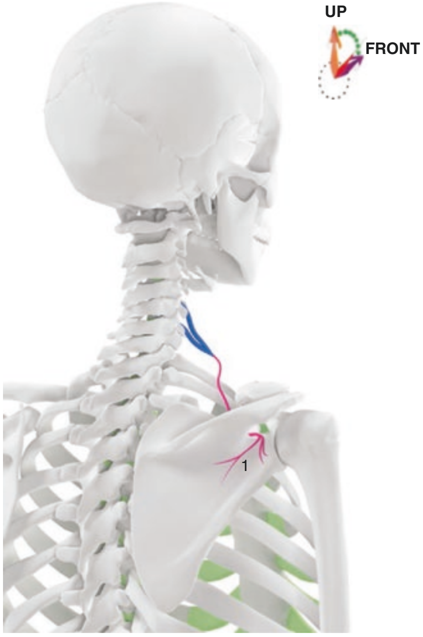


Figure SSc1. The suprascapular nerve's relations with bones.

Electronic Supplementary Material The online version of this chapter (https://doi.org/10.1007/978-3-030-49179-6_10) contains supplementary material, which is available to authorized users.

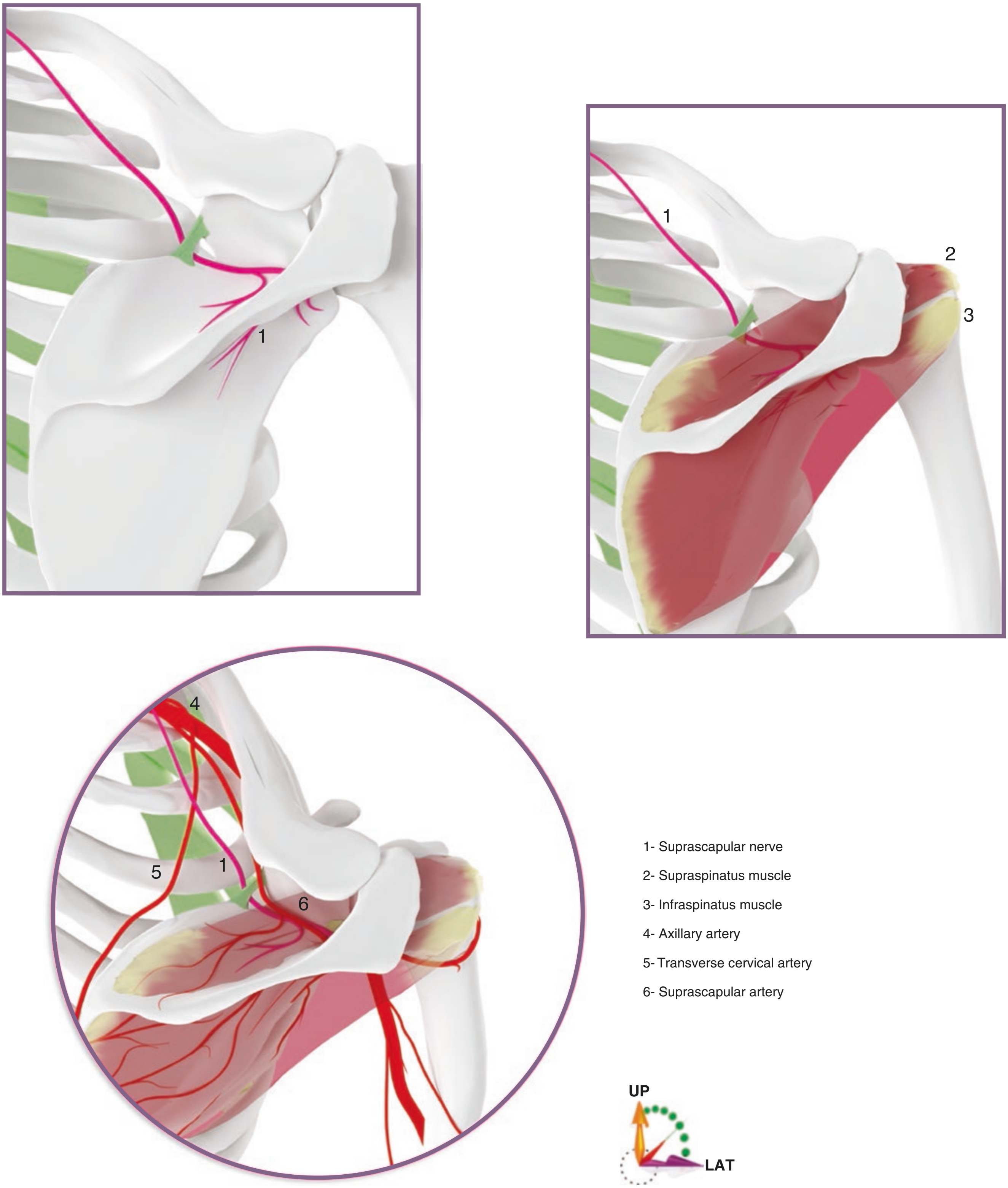

1
1
2
3
4
5
1
6
1- Suprascapular nerve
2- Supraspinatus muscle
3- Infraspinatus muscle
4- Axillary artery
5- Transverse cervical artery
6- Suprascapular artery
UP
LAT

Figure SSc2. Osteoligamentous and vascular relations of the suprascapular nerve.

1- Pectoralis major muscle

2- Pectoralis minor muscle

3- Cephalic vein

4- Deltoid muscle

5- Short head of the biceps brachii muscle

6- Coracobrachialis muscle

7- Tendon of the long head of the biceps brachii muscle

8- Latissimus dorsi muscle

9- Humerus

10- Teres major muscle

11- Lateral head of the triceps brachii muscle

12- Circumflex artery and nerve

13- Long head of the triceps brachii muscle

14- Teres minor muscle

15- Infraspinatus muscle

16- Scapula

17- Medial cutaneous nerve of arm

18- Median nerve

19- Medial cutaneous nerve of forearm

20- Ulnar nerve

21- Radial nerve

22- Musculocutaneous nerve

23- Subscapularis muscle

24- Serratus anterior

25- Intercostal muscles

26- Lateral thoracic artery

27- Suprascapular nerve

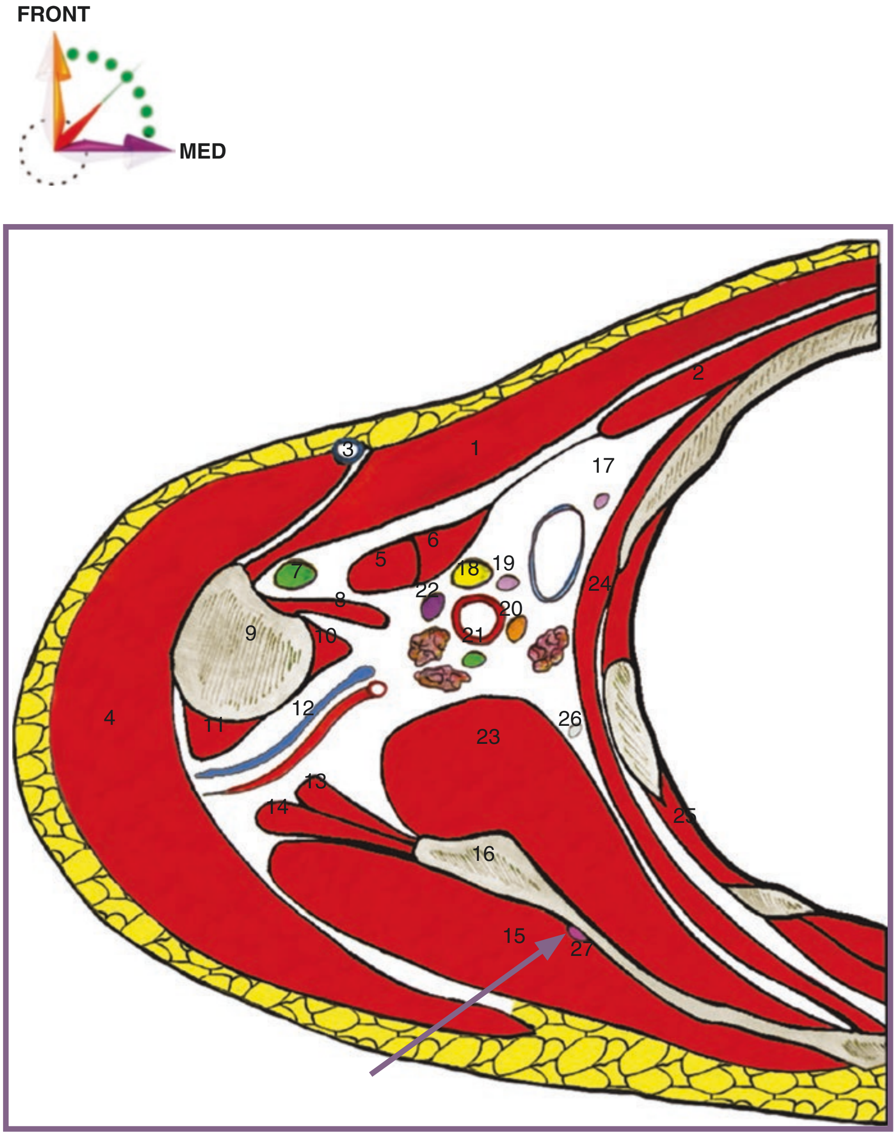


Figure SSc3. Axial section at axillary fossa through the suprascapular nerve.

Pathologies

It can be compressed in the case of entrapment neuropathy at the level of the suprascapular notch (Figures SSc4 and SSc5).

Aetiology

- Traction: The apparition of this syndrome is caused by micro-traumas: sport, professional activity, traumatic movements of retropulsion, some constitutional abnormalities and muscle imbalance problems such as those caused by trapezius palsy.
- Compression: A clavicle fracture can lead to an injury of the suprascapular nerve if the fracture concerns the lateral part of the clavicle, in its descending part, under the insertion of the trapezius muscle.
- In medial rotation movements of the arm, the part where the suprascapular nerve goes through the suprascapular notch is a high-sensibility area. This compression can generally be found in sportspersons or individuals who have a job requiring repeated shoulder movements.
- Section: A section of the nerve can happen during shoulder, clavicle, or scapular surgeries.

Clinical Significance

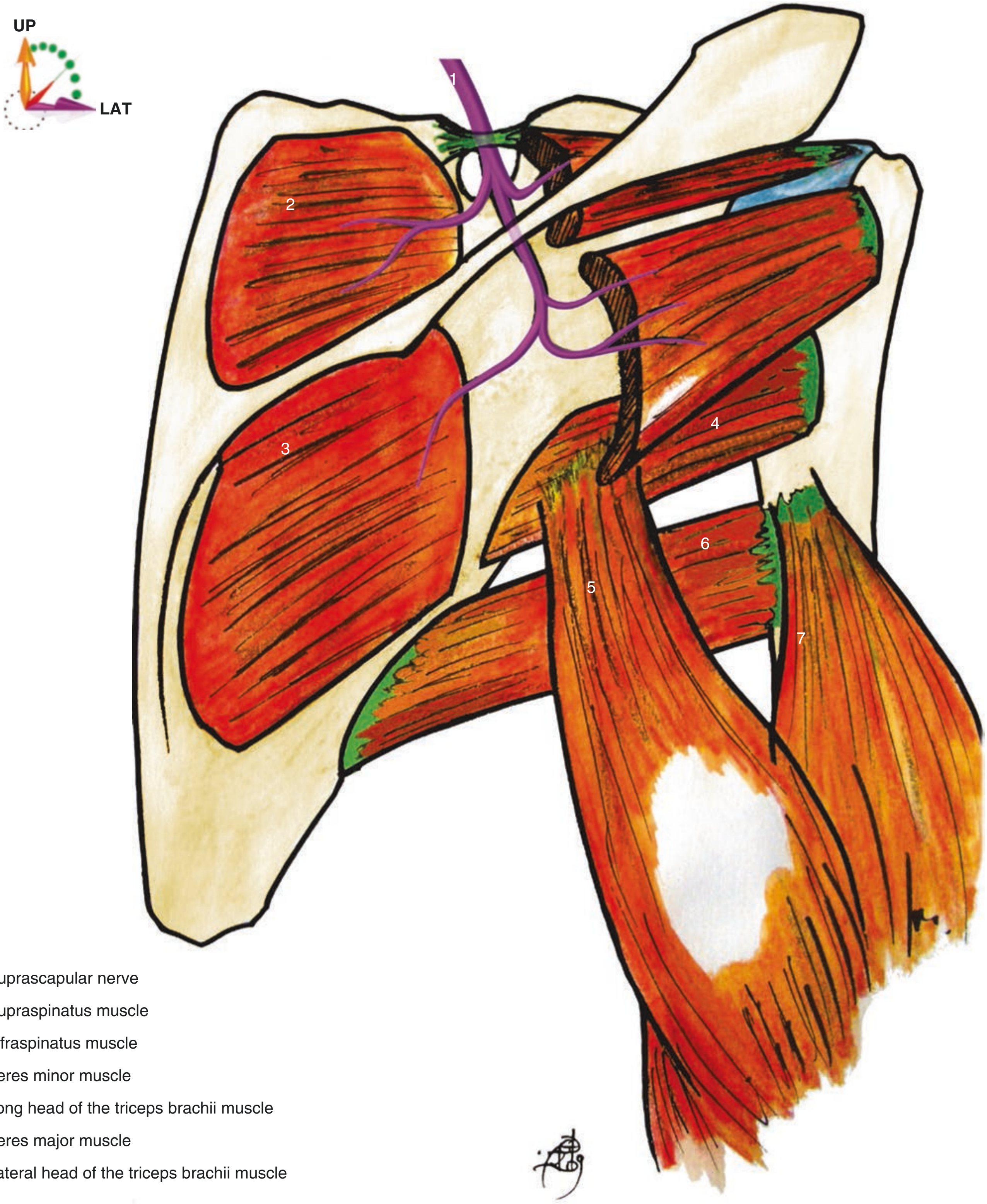
- Sensitive signs: The patient feels a dull, deep, shooting pain which exacerbates at night. Its first apparition can be sudden. The pain is situated in the posterolateral area of the shoulder and irradiates towards the acromioclavicular joint along the lateral border of the arm, towards the elbow, and can follow the radicular paths of C5 and C6. The pain is caused by cross body adduction and triggered by applying stress on the suprascapular joint, weakened by the elevation of the shoulder.
- Motor signs: Functional impairment is generally described as moderate. The motor deficit concerns the initial steps of the movement of abduction of the shoulder but not the whole movement, since the deltoid muscle is intact. It also becomes impossible for the patient to perform a complete lateral rotation. Another motor sign is a more or less extensive amyotrophy of the supraspinatus and infraspinatus muscles.

Explorations

- Shoulder and cervical spine radiographs are generally normal.
- Electroneuromyography: difficult to perform, but helps objectify an electrophysiological injury of the subscapular nerve.
- MRI and scanner can highlight an extrinsic compression.

Treatment

The first action should be a local corticosteroid infiltration. If this fails, treatment includes a surgical opening of the superior transverse scapular ligament and of the coracoacromial ligament sometimes associated with a removal surgery of an adenopathy which could worsen the compression. The result regarding pain is satisfying in 70% of cases. There is a better recovery for infraspinatus palsy than for supraspinatus palsy.



1. Suprascapular nerve
2. Supraspinatus muscle
3. Infraspinatus muscle
4. Teres minor muscle
5. Long head of the triceps brachii muscle
6. Teres major muscle
7. Lateral head of the triceps brachii muscle

Figure SSc4. Pathology of the suprascapular nerve: Anatomical structures going through the spine of the scapula near the surgical entry point (see following example).

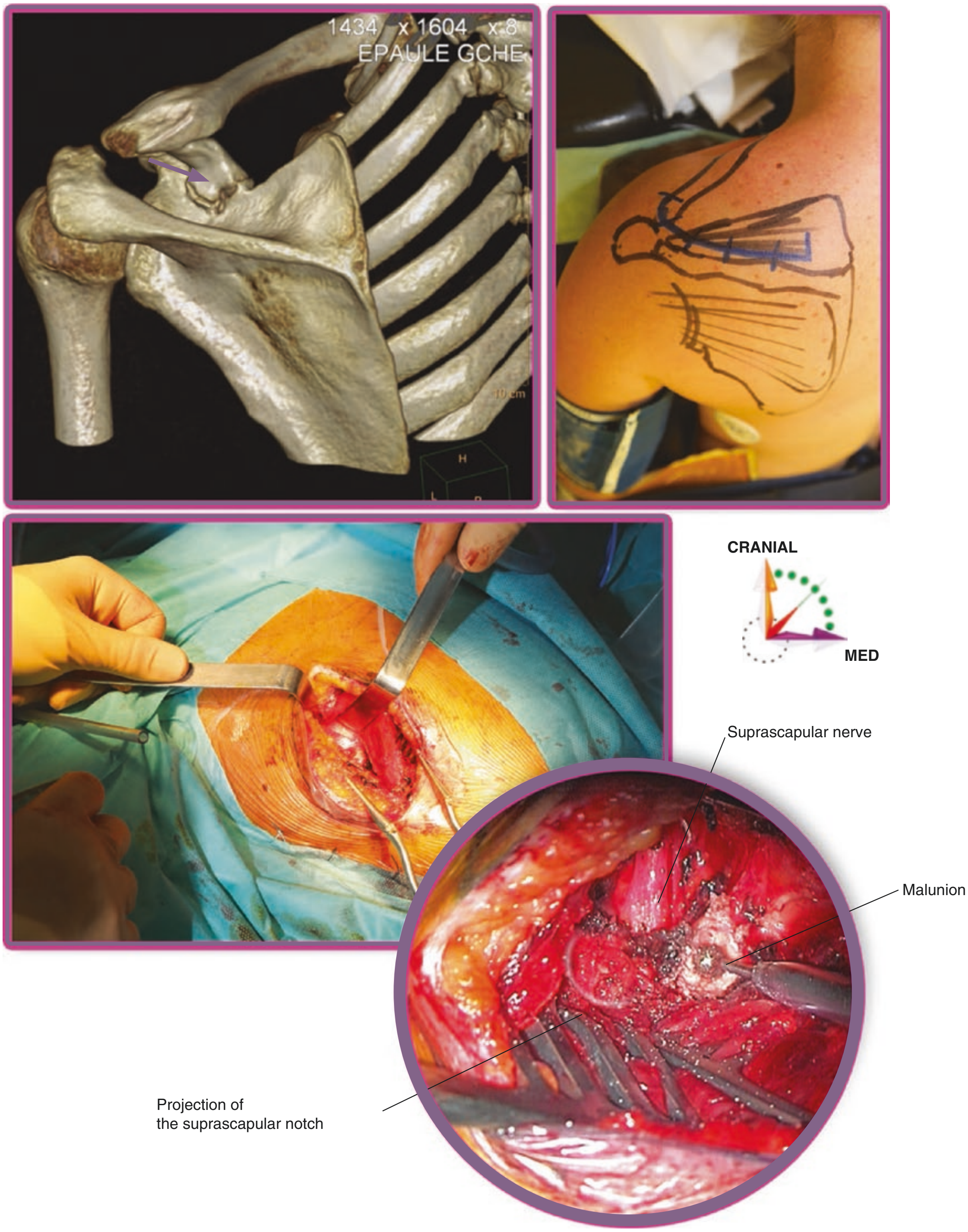

1434 x 1604 x 8
EPAULE GCHE
10 cm
H
CRANIAL
MED
Suprascapular nerve
Malunion
Projection of
the suprascapular notch

Figure SSc5. Case of a patient presenting a malunion after a fracture with important tilting of the left clavicle. The callus becomes a bridge between the lateral clavicular fragment and the spine of the scapula by ensheathing the suprascapular nerve at the level of the notch. This compression causes stitching pain in the shoulder which increases in intensity during rotation movements of the scapula; a disuse atrophy of the rotator cuff muscles with deficit of initiation of abduction of the shoulder can be noticed. A decompression surgery of the suprascapular nerve through suprascapular access has been suggested to this patient and allowed for a nerve release by partially milling the callus and the suprascapular notch.

Morphological Data: Sono Anatomy

In the supra-clavicular region, the suprascapular nerve leaves the plexus by crossing the deep surface of the omohyoid muscle, with a lateral-dorsal direction towards its fossa, the nerve then being relatively superficial.

Installation

The patient is in supine position, head in neutral position.

Equipment and Location

- Probe type: High frequency 5–12, 6–13 Hz.
- Probe axis: The probe is placed parallel to the clavicle in the supra-clavicular space to make an axial cut.

Ultrasound Procedure

The main landmarks are the plexus, the axillary artery, the anterior omohyoid muscle, with the suprascapular nerve being posterior to the omohyoid muscle and lateral to the plexus.

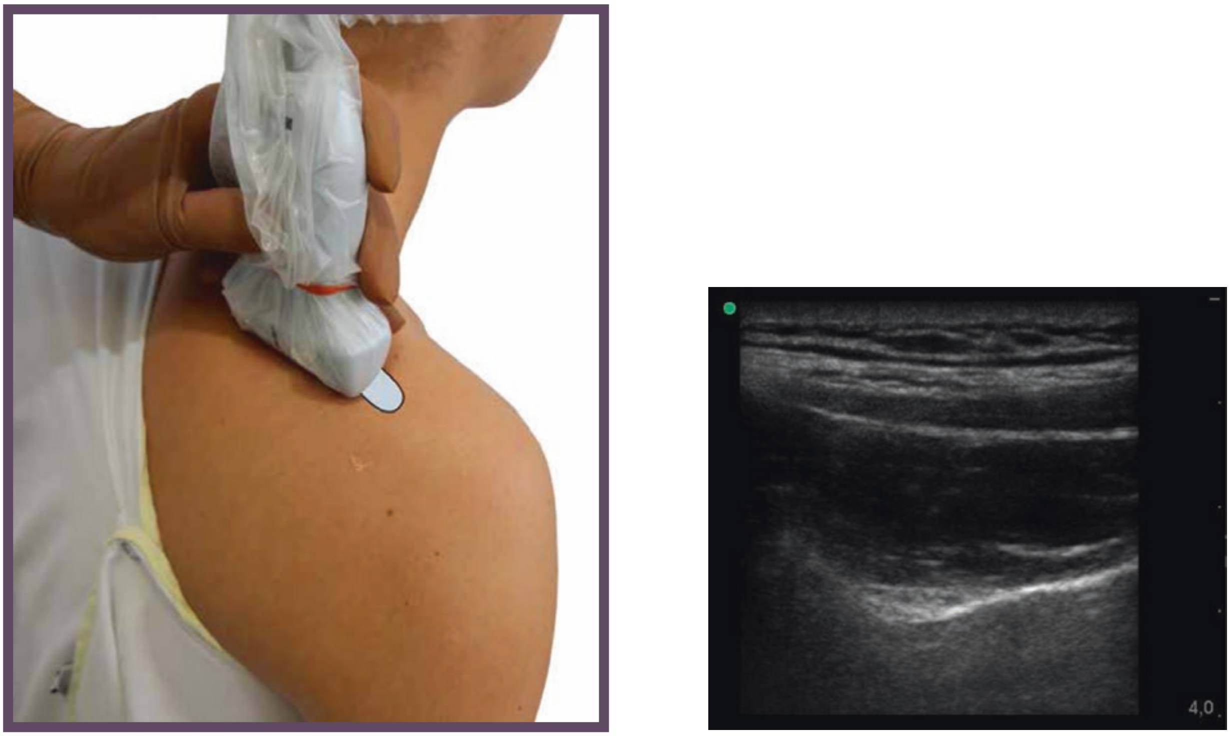


Figure SSc6. Ultrasound axial slices of the suprascapular nerve at the supraclavicular level.

At the suprascapular fossa, the suprascapular nerve travels between the suprascapular notch and the spinoglenoid notch. The anatomy of the scapula is very variable. The suprascapular incision is not found in 15% of cases. Despite the fact that the nerve is generally quite deep, a high-frequency linear probe is usually sufficient. More rarely, a low-frequency probe is necessary depending on the patient's build. The patient is either supine or seated, and the skin markers used are: the thorn of the scapula and the depression of the pit to the touch. The probe is positioned parallel to the spine at a slightly anterior direction. The landmarks are the trapezius and supraspinatus muscles, the spine of the scapula, the supraspinatus fossa and the suprascapular artery, which is sometimes visible.

It is interesting to follow the path of the suprascapular artery that travels above the superior transverse scapular ligament and then to the suprascapular notch. Once the supraspinous fossa is crossed, it joins the nerve more distally, at the level of the infraspinous fossa.

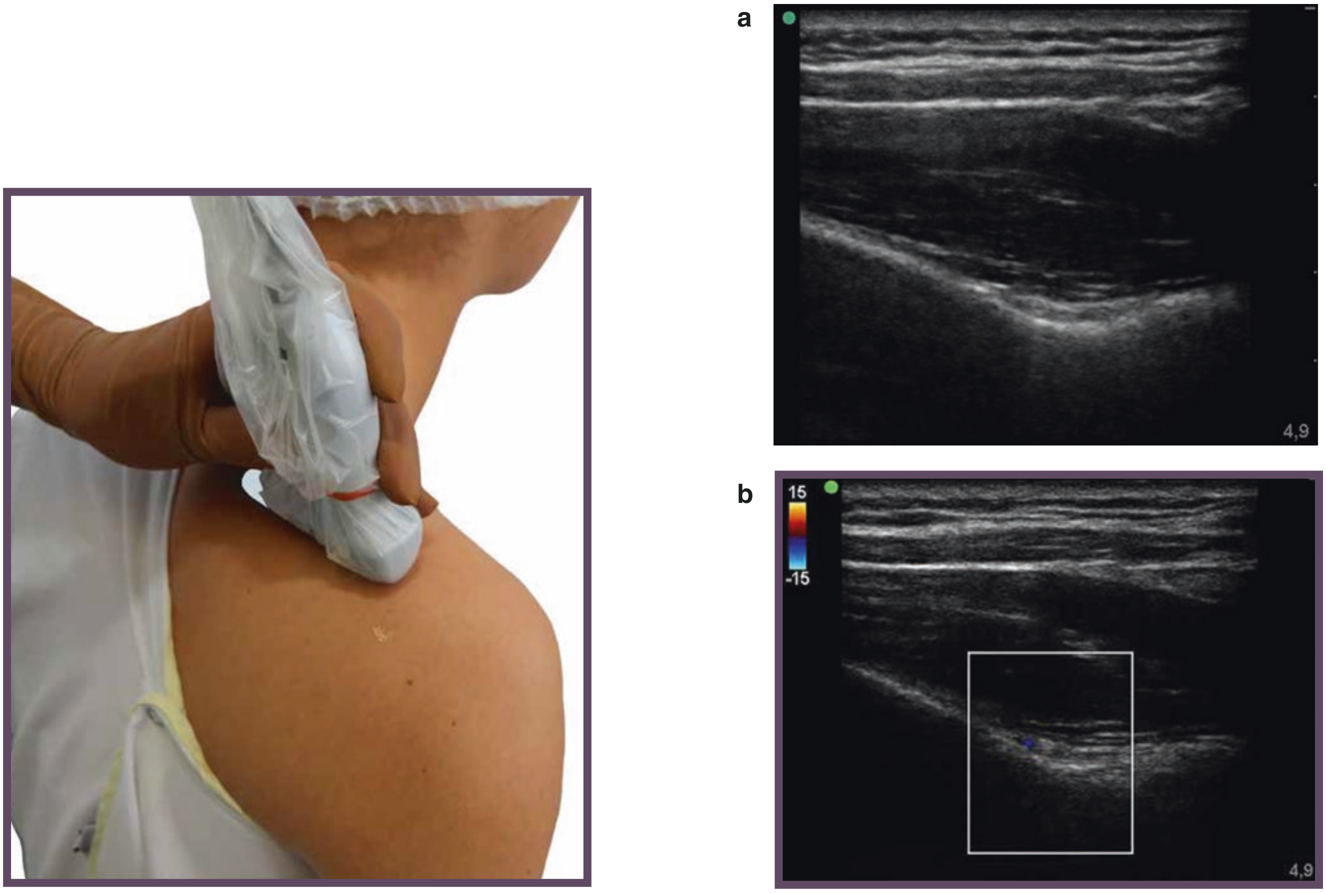


Figure SSc7. (**a**) Ultrasound axial slices of the suprascapular nerve at the suprascapular notch level. (**b**) Doppler mode view.

Interventional Procedure

Infiltration/Test Block

Whilst we prefer the supraspinous fossa as site of the infiltrative block, at the omohyoid muscle level, due to the proximity of the plexus, it is difficult to be very selective. The technique will be performed in plane, from medial to lateral, with hydrodissection to check the needle location. In case of a diagnostic block, hydrodissection will be performed with saline in small doses, unlike infiltration.

RFP

It is possible to perform a pulsed radio frequency on a conscious patient. The stimulation test is performed at 50 Hz, 1 ms, voltage below 0.45 V. A local anaesthetic injection follows the stimulation phase and then the radiofrequency phase itself is carried out, using the following parameters: 2 ms, 20 Hz, voltage at 45 V, thermocouple below 42 °C, for 3 min.

PNS

For the PNS technique, the installation position will be identical. The needle will be introduced into the ultrasound field (in plane) from medial to lateral. Hydrodissection is necessary given the depth of the nerve. Direct visualization of the needle is more random, and it is often more obvious when the superior transverse scapular ligament is lifted. Hydrodissection is performed with saline or glucose serum. It is advisable to carry out a preferably sensitive nerve stimulation test. If the patient's state of consciousness does not allow it, motor stimulation of the nerve (at low frequency, relatively low pulse duration and low intensity) is always possible, but it should be differentiated from direct stimulation of the suprascapular muscle fibres.

This technique is easy to perform with little risk, but a lead fracture is frequently observed in the months or years following the procedure, given the high mobility of the scapular belt and the resulting shearing movements. To reduce this risk, care should be taken to place the internal pulse generator as close as possible to the lead, either in the axillary or in the high lumbar region.

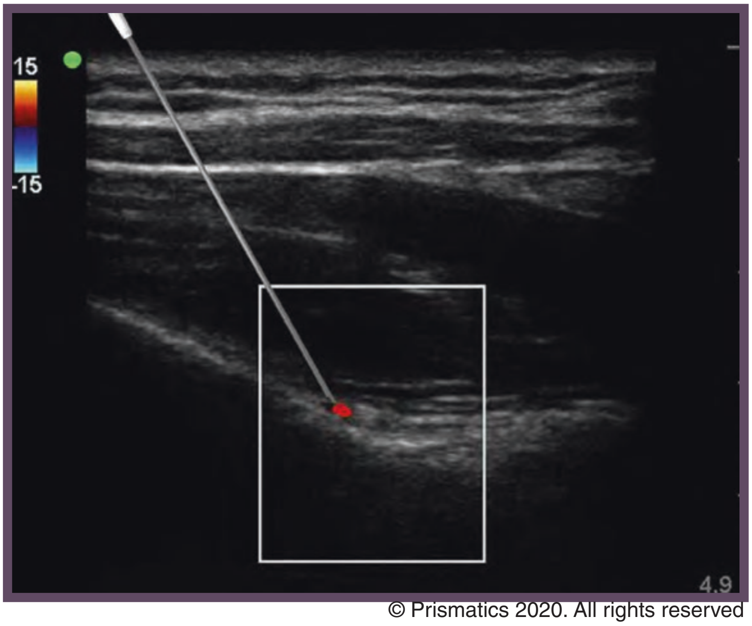


Figure SSc8. Ultrasound axial slice of the supraspinous fossa. Suprascapular nerve identification before lead implantation.

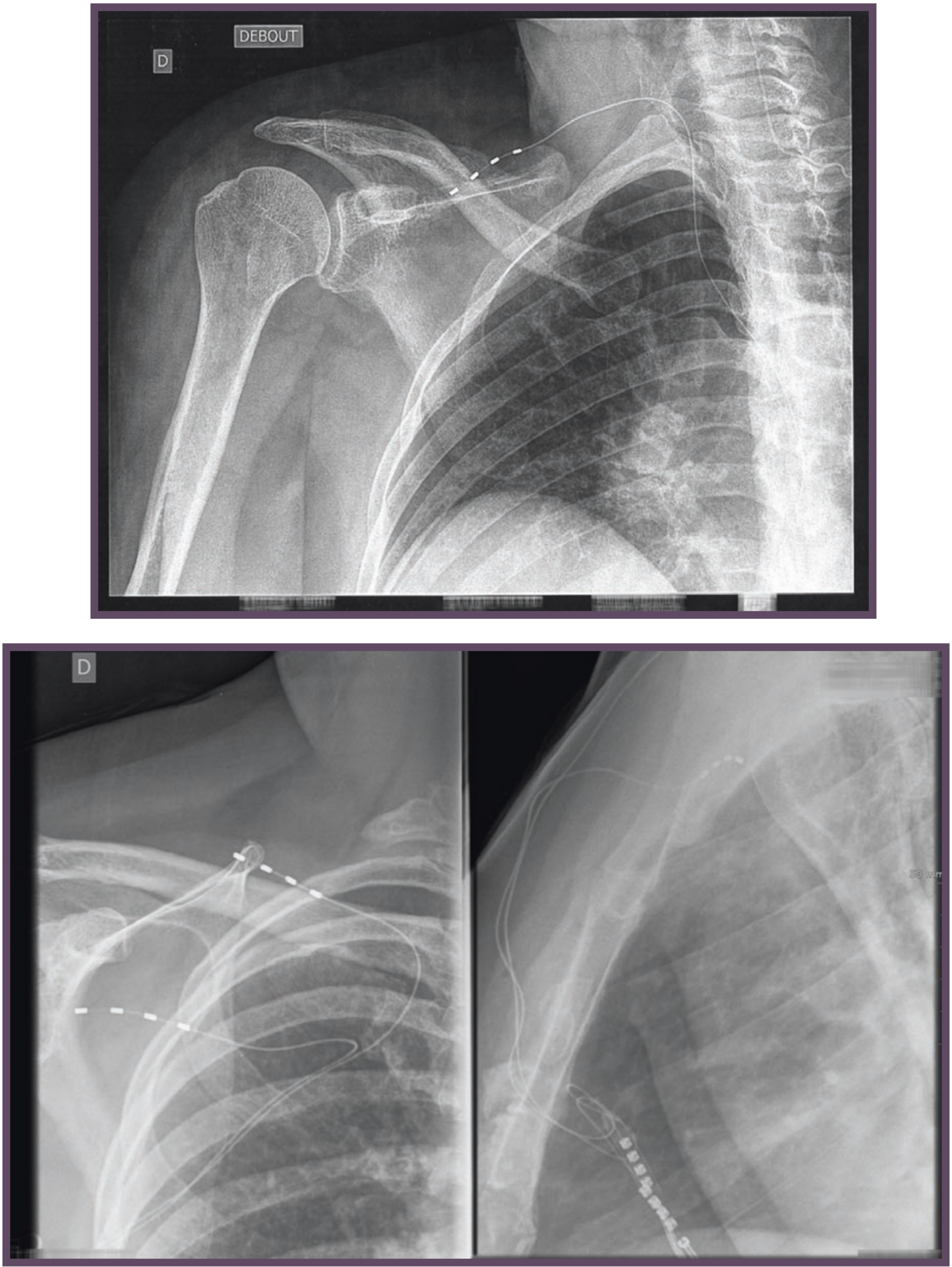


Figure SSc9. Post-op X-ray of a peripheral nerve stimulation (PNS), using a single and a double percutaneous approach of the suprascapular nerve.

Surgical Procedure

Surgical Approaches

Skin Incision

The surgical approach of the suprascapular nerve, at the border between the trunk and the upper limb, can frighten or confuse.

In fact, it is necessary to remain very close to the anatomy and therefore to the bone relief, in particular to the spine of the acromion so as to release this nerve on its supra or infraspinatus portion, depending on the underlying pathology. An arciform incision will therefore be made that curves at the junction of the spine and the scapula, at its internal edge, along the lateral insertion of the rhomboid muscles but remaining opposite the bone markers.

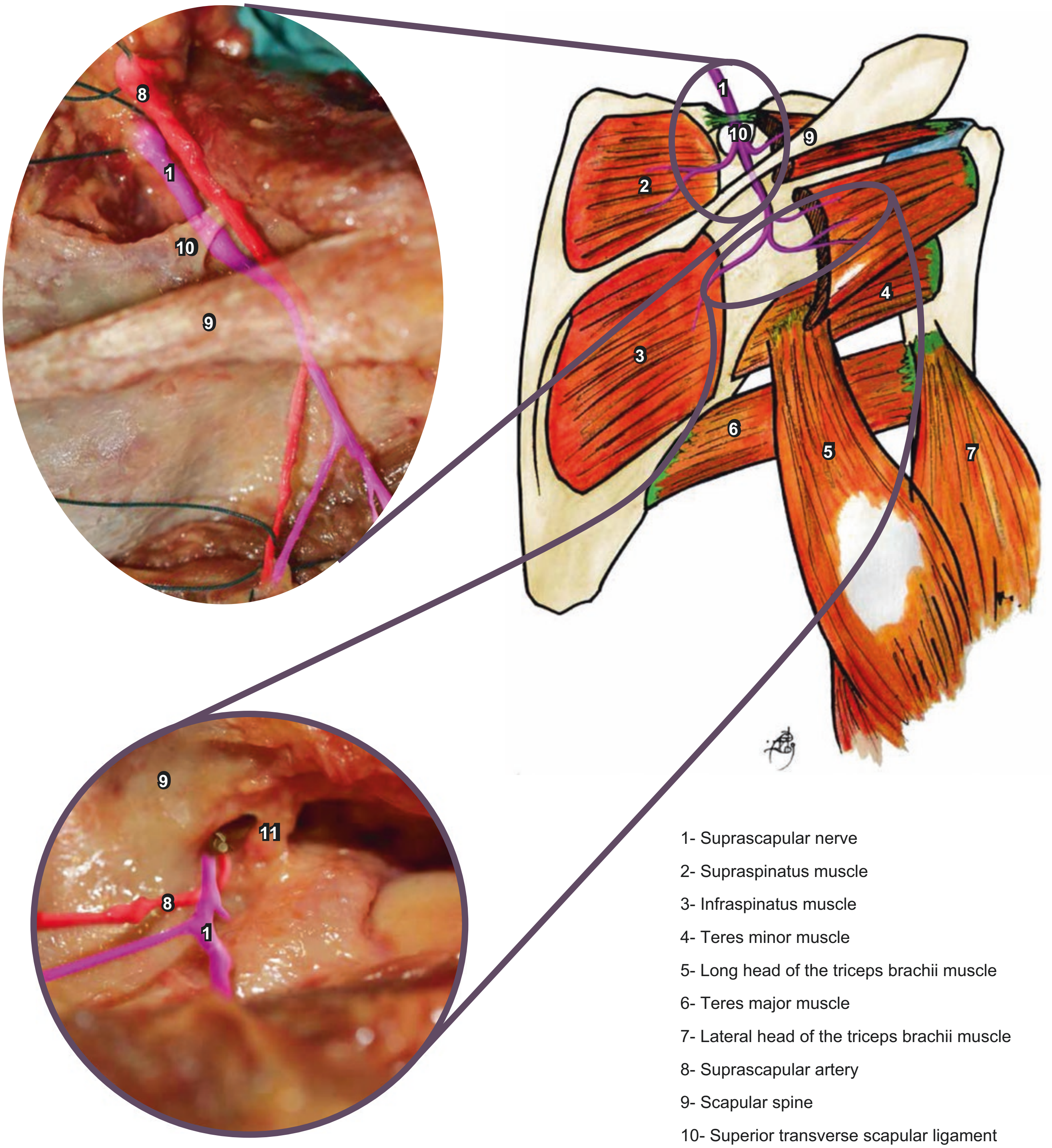
Nervous Exposure

If you wish to approach the nerve in its supraspinous portion (see illustration in pathology, Figure SSc10), certain fibres of the upper chief of the triceps brachii muscle will be removed as carefully as possible to access the fascia of the supraspinatus muscle, which will be reflexed upwards with a Faraboeuf retractor to go on its scapular insertion and gradually strip this pit with a Cobb rug, carefully, exposing the suprascapular vascular and nerve package. It is essential to preserve the innervation of the supraspinatus to avoid sequelae at the level of the cap, as well as its insertion towards the capsule. If you want to dive even further upstream of the nerve path, in order to expose the nerve at the suprascapular notch level, you can then pass between the triceps brachii muscle and the upper edge of the supraspinatus, which will be reflexed downwards to locate the notch.

The superior transverse scapular ligament can be severed, using the artery it crosses to clear the nerve over this supraspinous portion.

If one wishes to approach the nerve in its infraspinatus portion, it will then be necessary to disinsert and reflex the infraspinatus muscle outwards, remaining on the inner edge of the shoulder blade without diving into the underlying paravertebral gutter.

The nerve and its emergence can then be identified under the spine of the acromion, at the level of the infraspinatus fossa, where it will open out to achieve motor innervation of the infraspinatus muscle and uncheck its branch for the small circle. Closure will aim to restore each muscle plane, so that it remains as close as possible to the anatomy of this transitional region.



1- Suprascapular nerve
2- Supraspinatus muscle
3- Infraspinatus muscle
4- Teres minor muscle
5- Long head of the triceps brachii muscle
6- Teres major muscle
7- Lateral head of the triceps brachii muscle
8- Suprascapular artery
9- Scapular spine
10- Superior transverse scapular ligament
11- Inferior transverse scapular ligament

Figure SSc10. Suprascapular nerve dissection: anatomical structures narrowing the surgical approach at the level of the spine of the scapula (refer to “Pathologies” section).

The Long Thoracic Nerve

Morphological Data

The long thoracic nerve is a collateral motor branch of the brachial plexus, originating from its supraclavicular part.

Origin

It stems from the C5, C6 and C7 roots, shortly after they come out through the transverse foramina (Figure LT1).

Path

The long thoracic nerve goes down behind these previously mentioned roots, before the formation of the trunks of the plexus brachial. Then it generally pierces the scalenus medius muscle; the trunk of the nerve then emerges behind the clavicle and goes down the lateral chest wall in an oblique way, outside and below.

The second rib acts as a "sawhorse" as it travels vertically at this level and reaches the first digitation of the serratus anterior muscle. The latter covers the medial part of the axillary pit. The nerve then gives off a branch for each digitation of the serratus anterior muscle (Figure LT2).

Neurovascular Relations

In its thoracic part, the long thoracic nerve faces the lateral thoracic artery in behind (Figure LT2).

Terminal Branches

The long thoracic nerve ends when it gives off its motor fibres to the anterolateral face of the serratus anterior muscle.

Motor Function

The long thoracic nerve takes charge of the innervation of the serratus anterior muscle. This muscle ends on the medial border of the scapula and delimitates the inter-serrato-thoracic and inter-scapulo-thoracic spaces (Figure LT3). The long thoracic nerve finally takes charge of the functions of abduction, lateral rotation, depression as well as maintaining the scapula against the posterior wall of the ribcage.

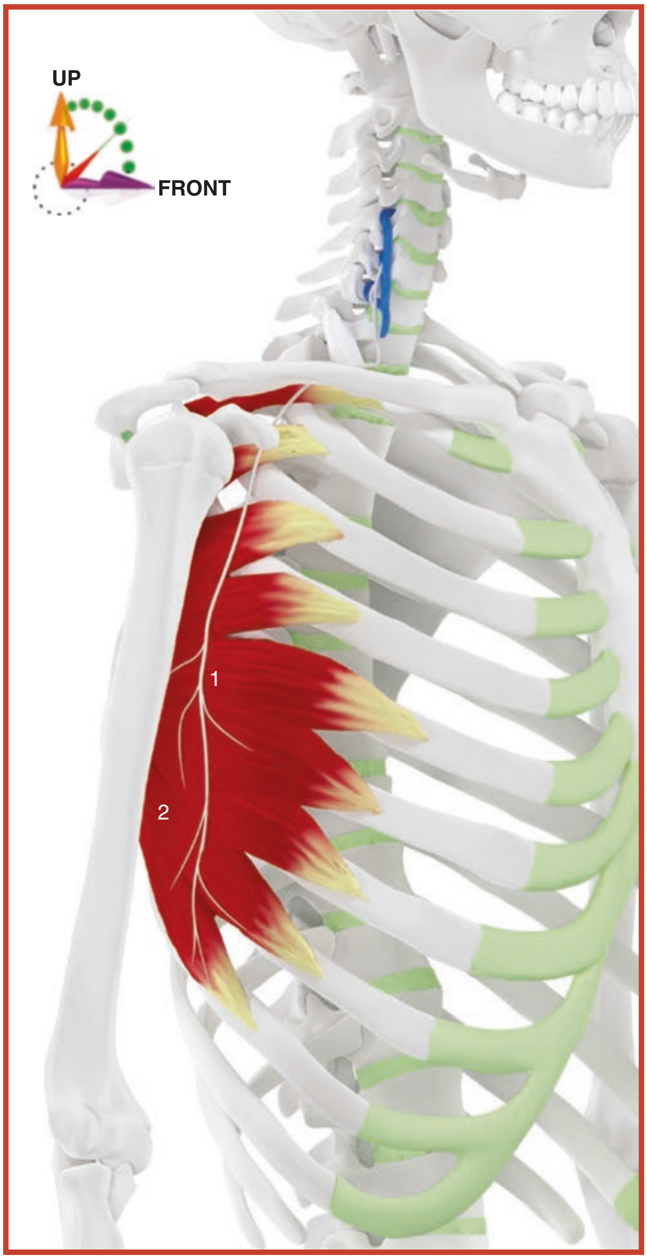


Figure LT1. Motor innervation of the long thoracic nerve and its relations with the bones.

Electronic Supplementary Material The online version of this chapter (https://doi.org/10.1007/978-3-030-49179-6_11) contains supplementary material, which is available to authorized users.

1- Long thoracic nerve
2- Serratus anterior
3- Lateral thoracic artery

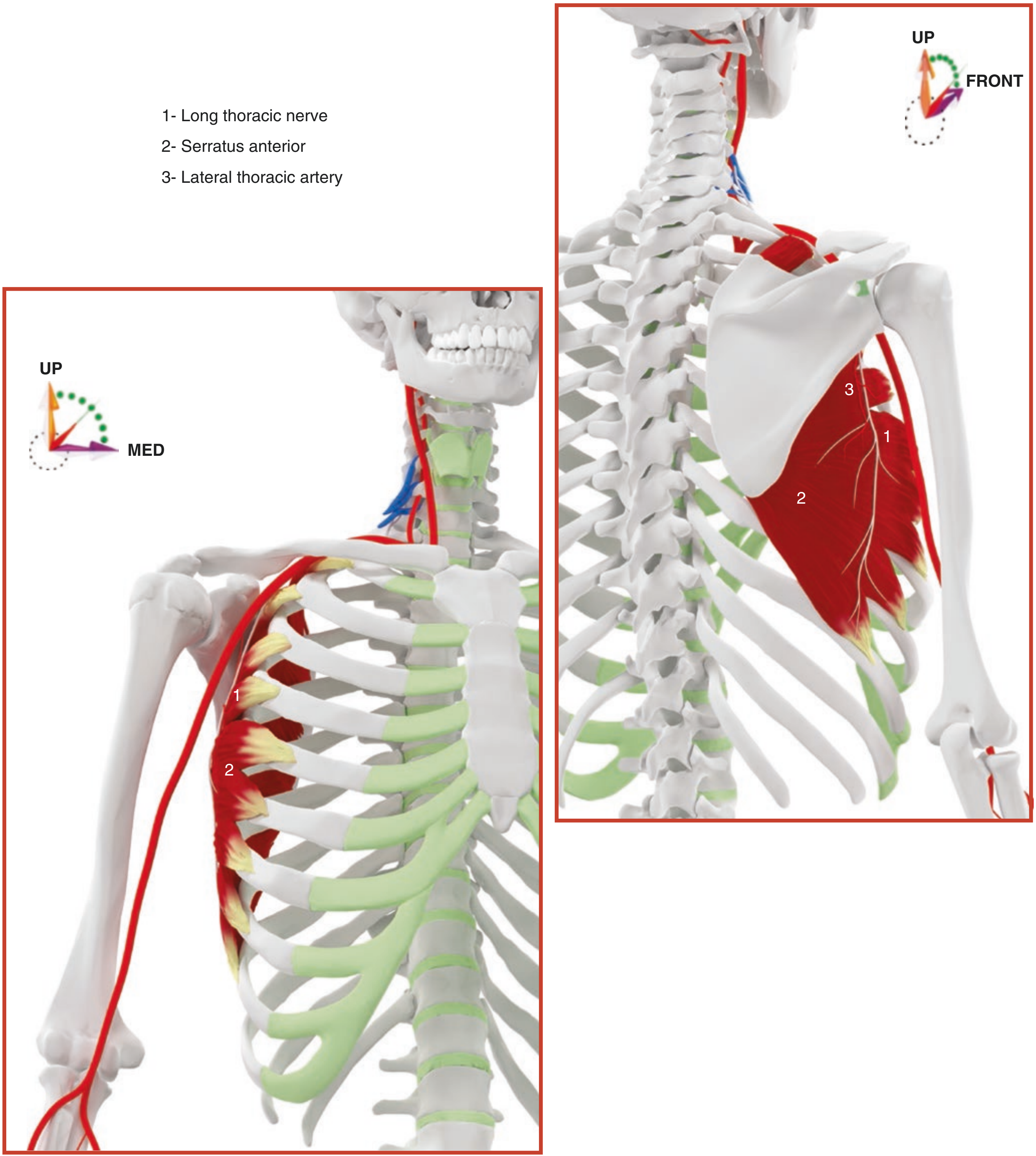

UP
FRONT
3
1
2
UP
MED
1
2

Figure LT2. Motor innervation of the long thoracic nerve and its relations with bones.

The Long Thoracic Nerve

1- Pectoralis major muscle

2- Pectoralis minor muscle

3- Cephalic vein

4- Deltoid muscle

5- Short head of the Biceps brachii muscle

6- Coracobrachialis muscle

7- Tendon of the long head of the Biceps brachii muscle

8- Latissimus dorsi muscle

9- Humerus

10- Teres major muscle

11- Lateral head of the triceps brachii muscle

12- Circumflex artery and nerve

13- Long head of the triceps brachii muscle

14- Teres minor muscle

15- Infraspinatus muscle

16- Scapula

17- Medial cutaneous nerve of arm

18- Median nerve

19- Medial cutaneous nerve of forearm

20- Ulnar nerve

21- Radial nerve

22- Musculocutaneous nerve

23- Subscapularis muscle

24- Serratus anterior

25- Intercostal muscles

26- Long thoracic nerve

27- Suprascapular nerve

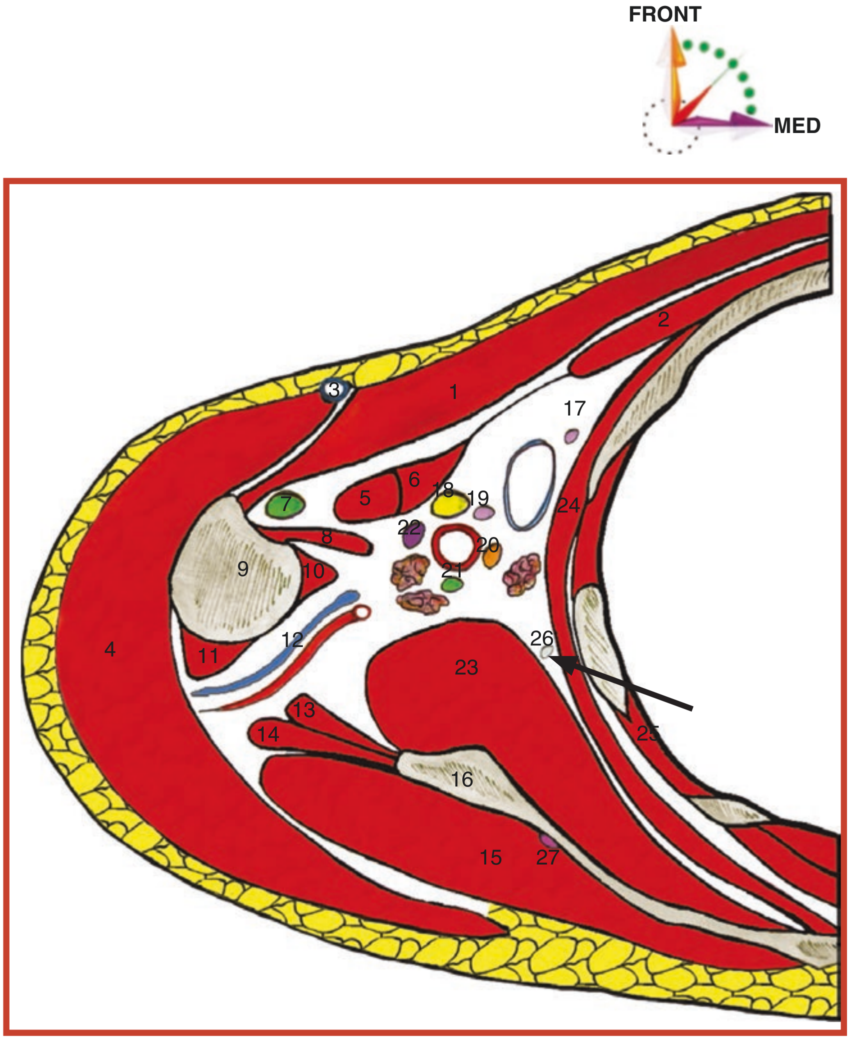


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Figure LT3. Axial section at axillary fossa through the long thoracic nerve.

Pathologies

The long thoracic nerve is weakened by its length and slenderness. It can move on the "sawhorse" of the second rib, where it changes direction with a 60° angle on average. It can be compressed and/or stretched in the case of a forced depression of the shoulder or of an excessive retropulsion, especially in some sports or occupations: repetitive lifting of heavy weights, throws, etc. Isolated palsy of the serratus anterior ordinarily affects young adults between 20 and 40 years old.

Aetiology

- Traction: It can happen whilst carrying heavy weights or in cases of shoulder injuries of sternum-clavicle dislocation type, or clavicle fracture. Repeated movements with lateral extension or rotation, or even shoulder protraction, can also injure the long thoracic nerve.
- Compression: It can be positional, especially during general anesthesia, when the arm is placed under the patient's thorax.
- Section: An isolated injury of the long thoracic nerve can be seen in most cardiothoracic surgeries.

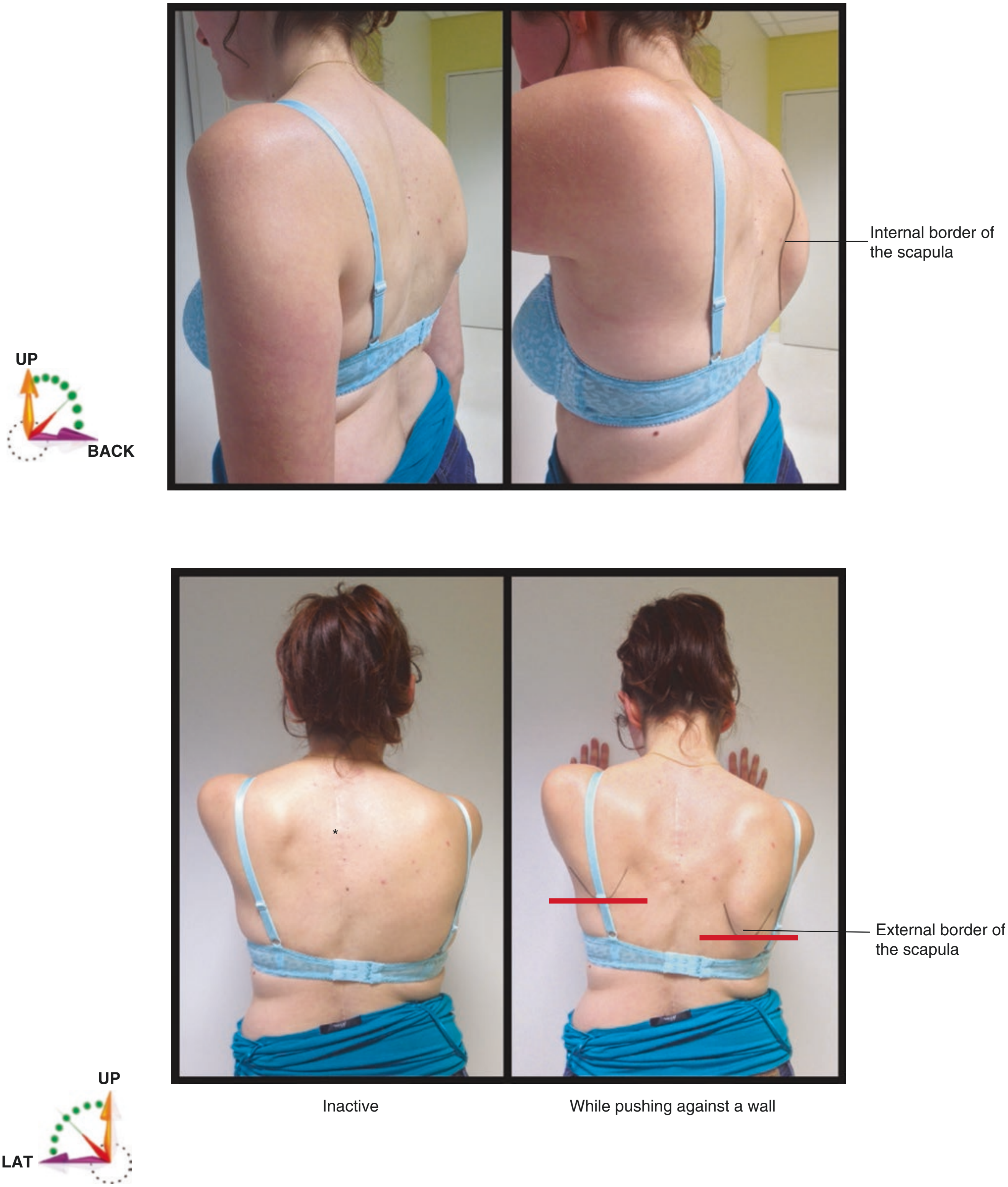
Clinical Significance

- Sensitive signs: A sudden parascapular thoracic pain, often during night-time, appears within a few hours after physical exercise. The pain's location can vary, sometimes radiating to the upper limb.
- Motor signs: The medical practitioner can search for a winged scapula or "scapula alata" by making the patient press both the hands flat against a wall. This can often show a unilateral bump on the spinal border of the scapula instead of a complete tilt (Figure LT4).

Treatment

Rest and suppression of the triggering events can generally allow the nerve to heal, but the process is slow, requiring between 6 and 18 months.

A direct surgery at the level of the nerve is not advised. In the case of persisting paralysis, several orthopaedic surgery techniques of scapular stabilization can be suggested as a palliative solution.


Internal border of the scapula
UP
BACK
*
External border of the scapula
UP
LAT

Inactive

While pushing against a wall

Figure LT4. Case of a patient showing a scapula alata caused by a direct injury of the long thoracic nerve after a scoliosis surgery with combined approach, including a posterior approach and a right thoracotomy.

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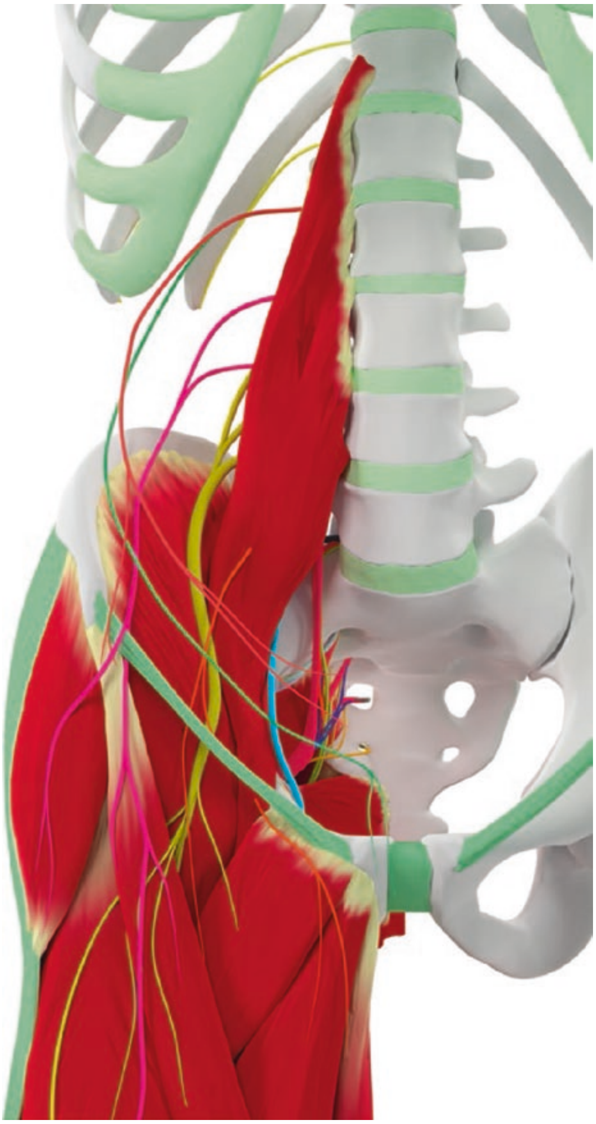
Part III

NERVES OF THE LOWER LIMB

THE LUMBOSACRAL PLEXUS



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Morphological Data

The innervation of lower limbs is controlled by the lumbosacral plexus.

The Lumbar Plexus

The lumbar plexus is made up of the union of the anterior branches of the four first lumbar spinal nerves. This connection occurs between the corporeal insertion (in front) and the costotransverse head of the psoas muscle (behind), at the level of the transverse apophyses of the lumbar vertebrae. In more than half of the cases, a ramification from T12 also participates to the constitution of the lumbar plexus. At its origin, the lumbar plexus is a triangle shape that widens laterally as one looks further away from its origin. It goes through the iliopsoas muscle and then faces the kidney in front and the quadratus lumborum muscle behind.

The ventral ramus of L1 splits into three branches: an upper branch, making the iliohypogastric nerve; an intermediate branch, making the ilioinguinal nerve; and a lower branch, merging with the ventral ramus of L2 to constitute the genitofemoral nerve.

The ventral ramus of L2 divides into four branches participating in the formation of the genitofemoral nerve (having an anastomosis with a branch of the ventral ramus of L1), lateral femoral cutaneous nerve (having an anastomosis with a ramus from L3), obturator nerve and femoral nerve.

The ventral ramus of L3 divides into three branches: the ramus anastomotic with L2 that forms the lateral femoral cutaneous nerve, a branch that innervates the femoral nerve and another for the obturator nerve.

The ventral ramus of L4 divides into three branches: a branch that makes up the femoral nerve, a branch that constitutes the obturator nerve and a branch that makes an anastomosis with the ventral ramus of L5 and forms the lumbosacral trunk, which is the terminal branch of the lumbar plexus (Figure LP1).

Along its short path, the lumbar plexus gives off some ramifications headed towards the adjacent muscles, in particular the quadratus lumborum and iliopsoas muscles in behind and psoas minor in front.

In total, the lumbar plexus gives off three important branches for the innervation of the lower limbs (Figure LP2):

- The obturator nerve (union of the most anterior ventral branches of L2, L3 and L4)
- The femoral nerve (union of the most posterior ventral branches of L2, L3 and L4 and whose bulkiest divisions undergo an anastomosis in order to constitute this nerve)
- The lateral femoral cutaneous nerve (made up of the thinnest branches of the previously mentioned divisions)

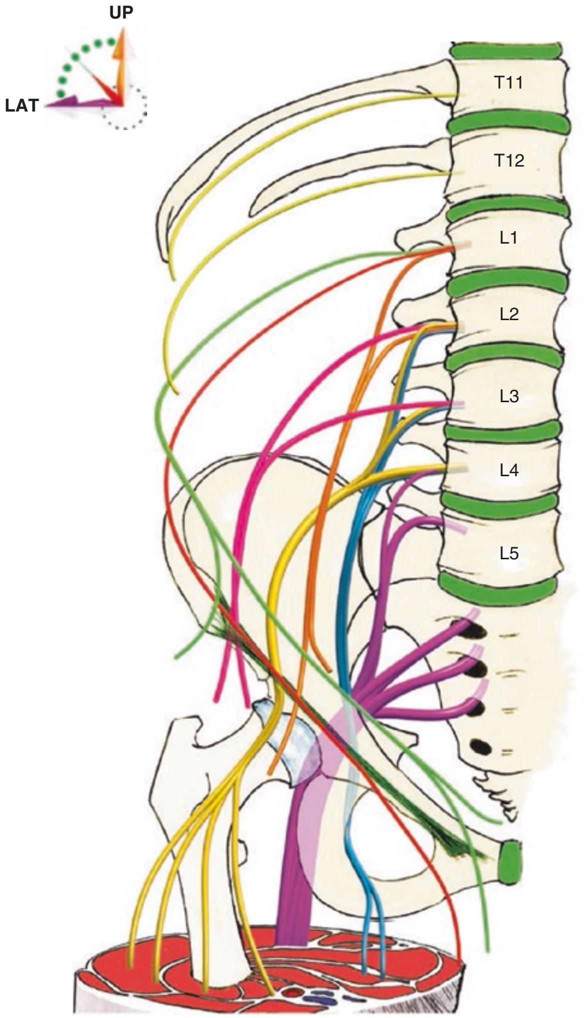

Figure LP1. Global view of the lumbosacral plexus.

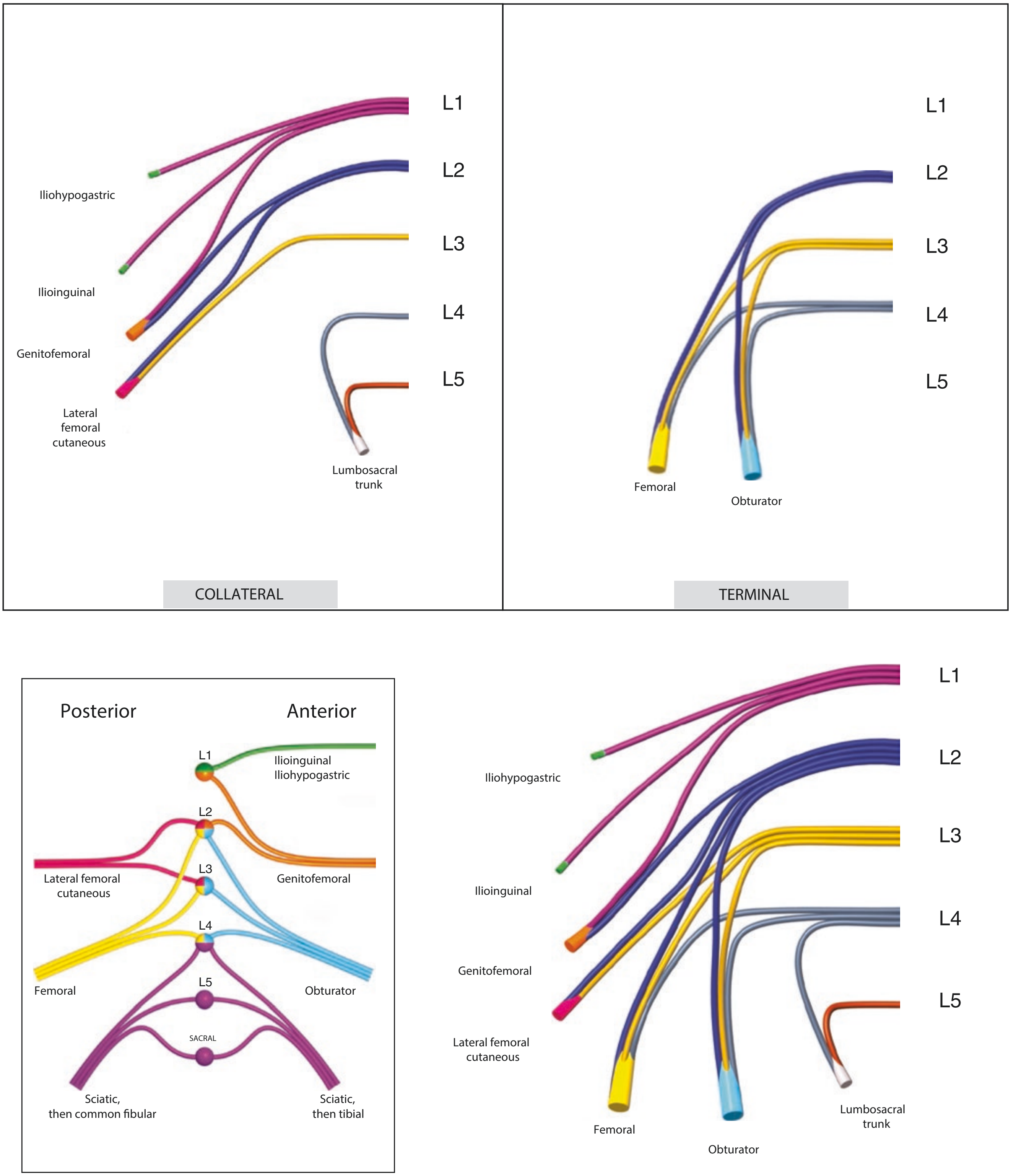
L1
L2
L3
L4
L5
Iliohypogastric
Ilioinguinal
Genitofemoral
Lateral femoral cutaneous
Lumbosacral trunk
COLLATERAL
L1
L2
L3
L4
L5
Femoral
Obturator
TERMINAL
Posterior
Anterior
L1
Ilioinguinal
Iliohypogastric
L2
Lateral femoral cutaneous
L3
Genitofemoral
L4
Femoral
L5
Obturator
SACRAL
Sciatic, then common fibular
Sciatic, then tibial
L1
L2
L3
L4
L5
Iliohypogastric
Ilioinguinal
Genitofemoral
Lateral femoral cutaneous
Femoral
Obturator
Lumbosacral trunk

Figure LP2. Origin of the branches of the lumbar plexus.

The Lumbosacral Plexus

The Sacral Plexus

The fibres from the ventral ramus of L4 merge with L5 to create the lumbosacral trunk. The latter emerges from the medial face of the psoas, goes in front of the sacroiliac joint and then penetrates the pelvis and participates in the constitution of the sacral plexus. It is situated in front of the piriformis muscle, at the level of the posterior wall of the pelvis. It comes from the union of the lumbosacral trunk with the anterior rami of the sacral nerves that come out of the sacral foramina which go down and merge into a main trunk.

The sacral plexus is made up of the union of the first three sacral roots of the lumbosacral trunk.

It then divides into:

- The actual sacral plexus (L4–S3), responsible for the innervation of the lower limbs and of the pelvic girdle
- The pudendal plexus (S2–S4), specifically dedicated to the innervation of the perineum (including external genitalia) and of the pelvic viscera

The greater portion of the ventral rami of S1, S2 and S3 merge with the lumbosacral trunk and form the sciatic nerve (Figure LP4).

The lumbosacral plexus gives off several collateral branches (Figure LP3):

- At the level of the anterior branches, there are the obturator internus nerve, the nerves that innervate the superior and inferior gemellus muscles and the nerve to the quadratus femoris.
- At the level of the posterior branches, there are the nerve to the piriformis, the superior gluteal nerve (for the gluteus minimus and medius as well as the tensor fasciae latae), the inferior gluteal nerve (for the gluteus maximus) and the posterior cutaneous femoral nerve. This sensitive nerve made up of nerve fibres coming from S1, S2 and S3 (Figure LP4). It comes out of the pelvis through the infrapiriform foramen and gives off a gluteal branch, the inferior cluneal nerves, a perineal branch and cutaneous ramifications for the posterior face of the thigh, the popliteal fossa and the posterior fossa of the leg in relation to the inter-gastrocnemius compartment.

The lumbosacral plexus makes anastomoses with the pudendal plexus and the pelvic sympathetic ganglia.

As an insight on history, the most detailed inventory of the variations of the constitution of the lumbar plexus has been written by Bonniot in 1922; it describes most of the classical variations. Statistical data that is this old are difficult to handle and to extrapolate, although it is observable that about a third of the dissected lumbar plexuses in this book showed a cranial or a caudal extension in their constitution.

This first description of the variations of the constitution of the lumbar plexus has been used as a base in the global apprehension of the subsequent descriptions. Sherrington described the pre-fixed and post-fixed plexuses, Langley mentioned and classified the anterior and posterior plexuses, and Bardeen and Etling made a semantic difference by mentioning the proximal, median and distal plexuses.

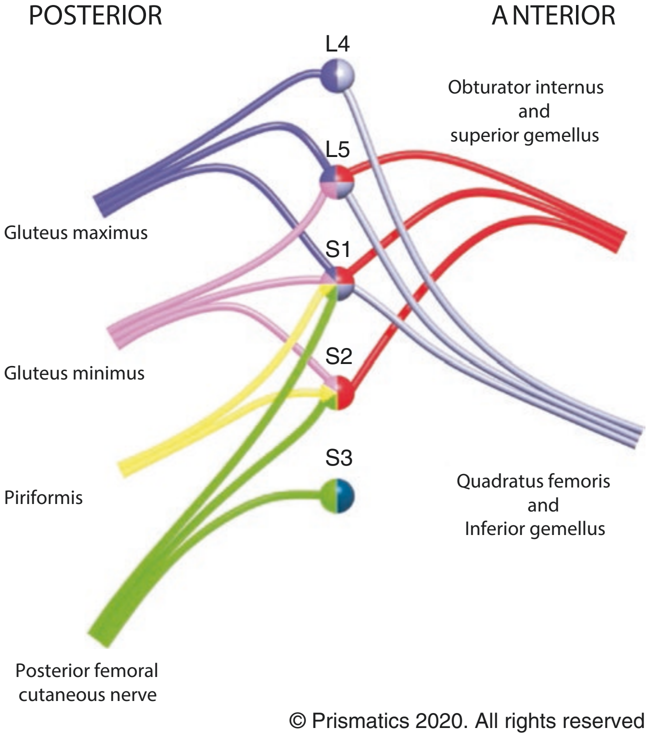

Figure LP3. Origin of the collateral branches of the sacral plexus.

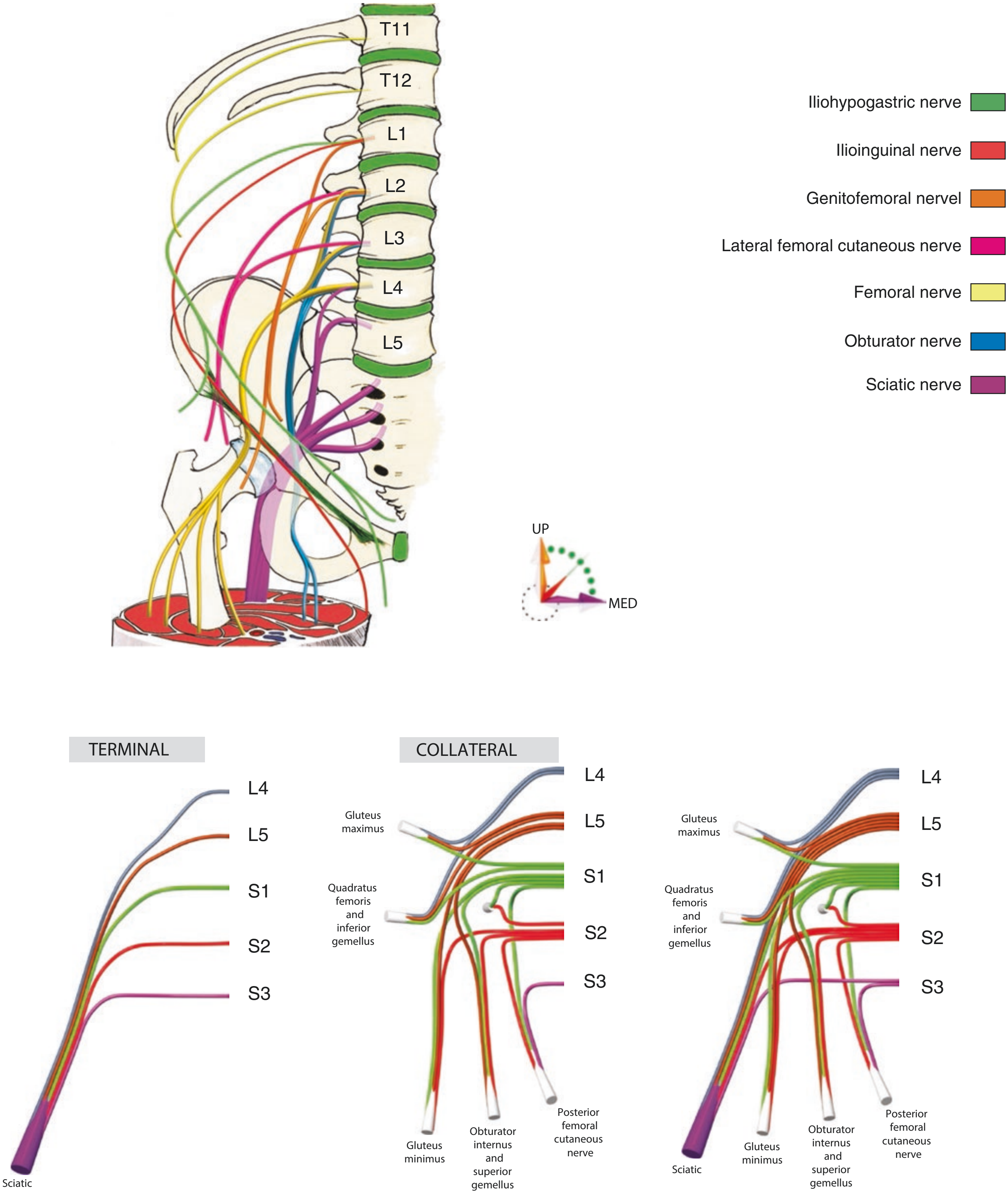
T11
T12
L1
L2
L3
L4
L5
Iliohypogastric nerve 🟩
Ilioinguinal nerve 🟥
Genitofemoral nervel 🟧
Lateral femoral cutaneous nerve 🟥
Femoral nerve 🟨
Obturator nerve 🟦
Sciatic nerve 🟪
UP
MED
TERMINAL
L4
L5
S1
S2
S3
Sciatic
COLLATERAL
L4
L5
S1
S2
S3
Gluteus maximus
Quadratus femoris and inferior gemellus
Gluteus minimus
Obturator internus and superior gemellus
Posterior femoral cutaneous nerve
L4
L5
S1
S2
S3
Gluteus maximus
Quadratus femoris and inferior gemellus
Sciatic
Gluteus minimus
Obturator internus and superior gemellus
Posterior femoral cutaneous nerve

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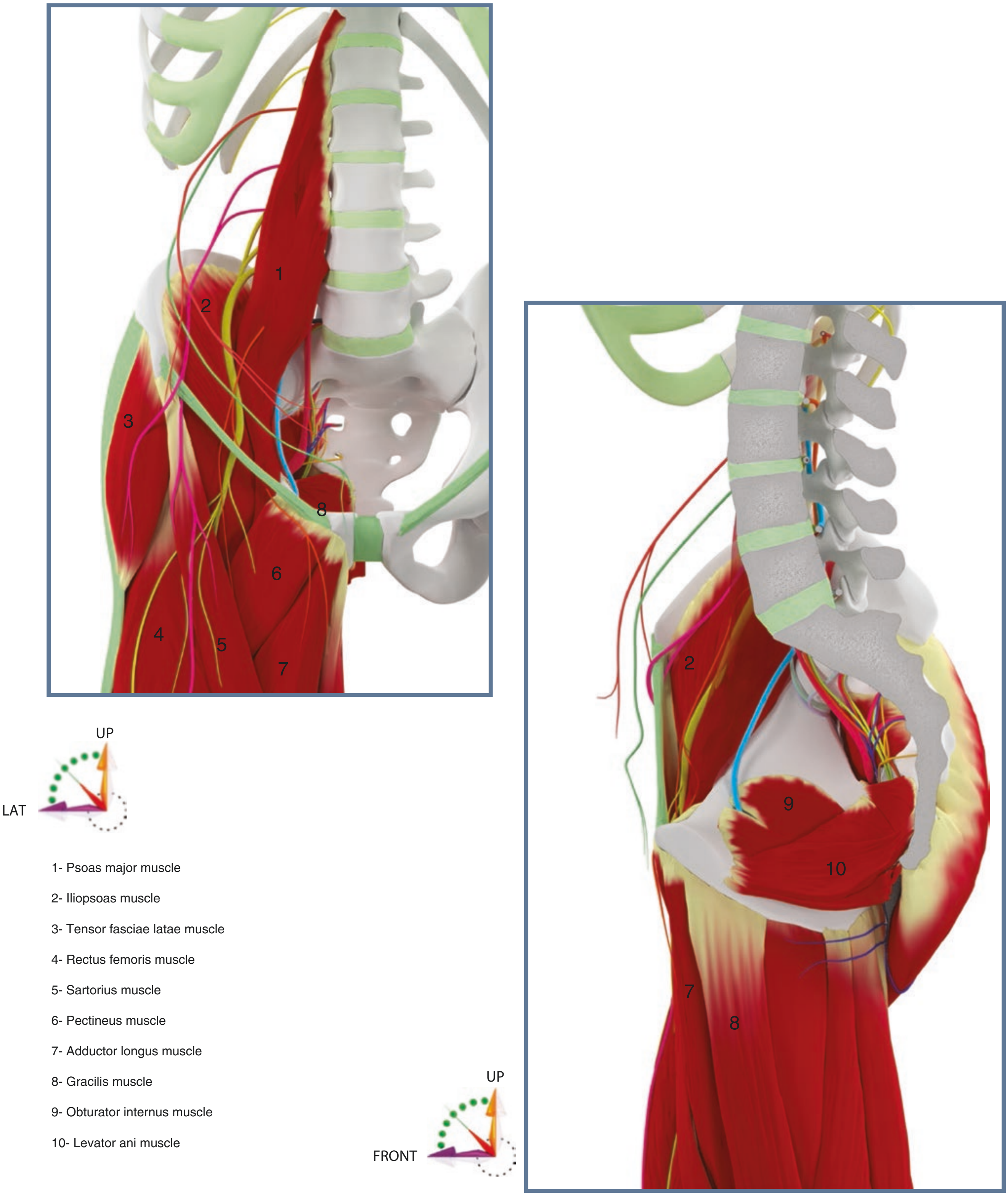
Figure LP4. The sacral plexus.

After the emergence of the roots from the intervertebral foramina and the formation of the trunks of the plexus, these trunks go in front of the transverse apophyses of the second, third and fourth lumbar vertebrae.

For the lumbar part, the branches of the plexus are in a close relationship with the two heads of the psoas major muscle, between which the ascending lumbar vein runs. This vein goes in front of the L5 and L4 ventral rami, then goes upwards and places itself, in most cases, behind the ventral rami of L2 and then of L1 (Figures LP5, LP6, LP7, LP8 and LP9).

For the sacral part, the plexus is covered by the parietal pelvic fascia and faces the internal iliac vessels and the ureter in front. The vascular relationships are essentially on the arterial level (the superior gluteal artery for the lumbosacral trunk and S1, the inferior gluteal artery for L2 and S3 and the lateral sacral artery in front of S1 for the internal pudendal artery below the plexus). The iliolumbar vein goes between the two roots of the lumbosacral trunk and then heads behind the lumbar plexus to get around it.



1- Psoas major muscle

2- Iliopsoas muscle

3- Tensor fasciae latae muscle

4- Rectus femoris muscle

5- Sartorius muscle

6- Pectineus muscle

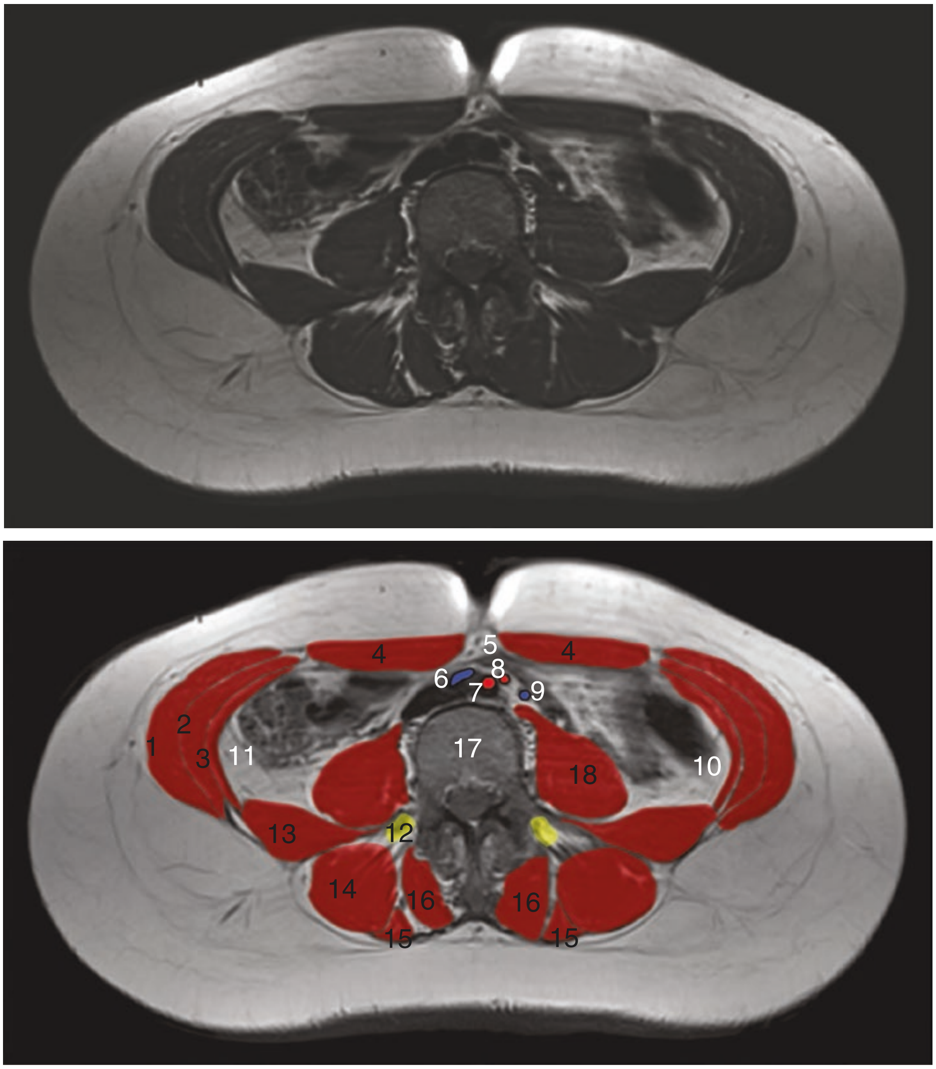
7- Adductor longus muscle

8- Gracilis muscle

9- Obturator internus muscle

10- Levator ani muscle

Figure LP5. Main muscular relations of the lumbar and sacral plexus.



1- Right external oblique muscle
2- Right transverse abdominis muscle
3- Right internal oblique muscle
4- Rectus abdominis muscles
5- Linea alba
6- Right common iliac vein
7- Right common iliac artery
8- Left common iliac artery
9- Left common iliac vein

10- Left colon
11- Right colic flexure
12- Right lumbar plexus
13- Right quadratus lumborum muscle
14- Right iliocostalis muscle
15- Longissimus muscles
16- Erector spinae muscles
17- 5th lumbar vertebra (L5)
18- Left psoas major muscle

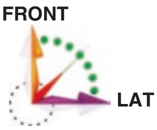
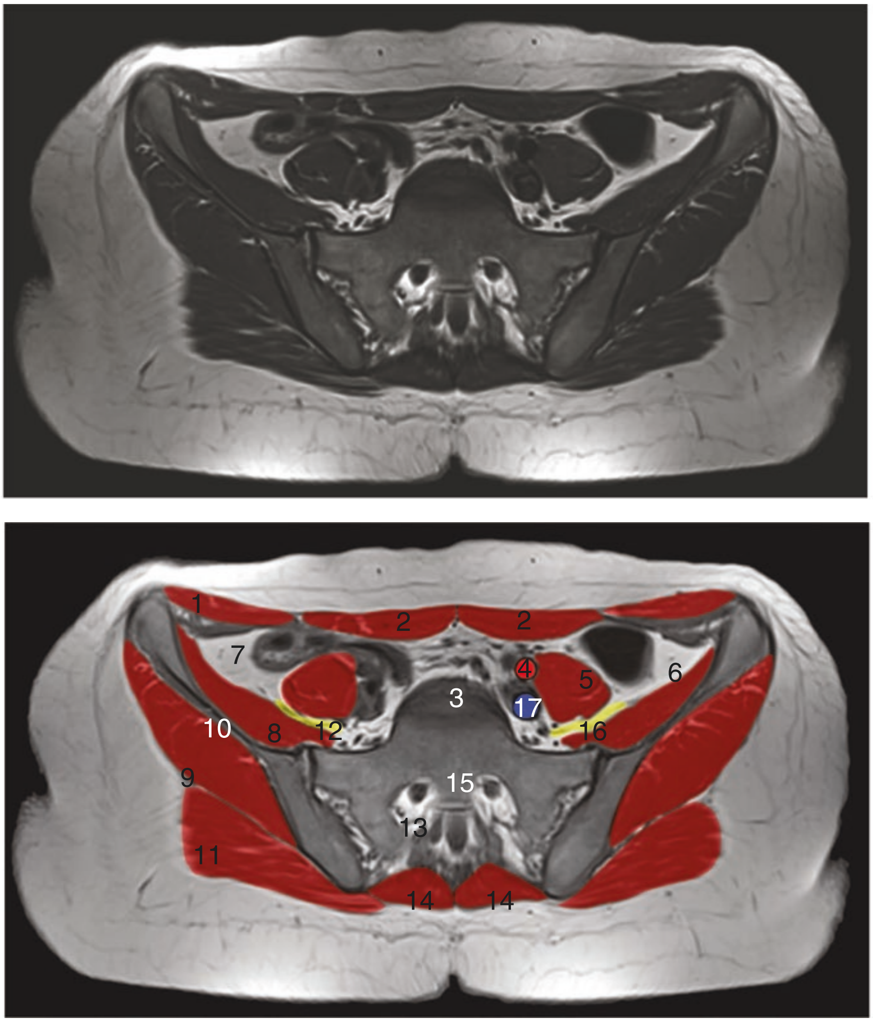


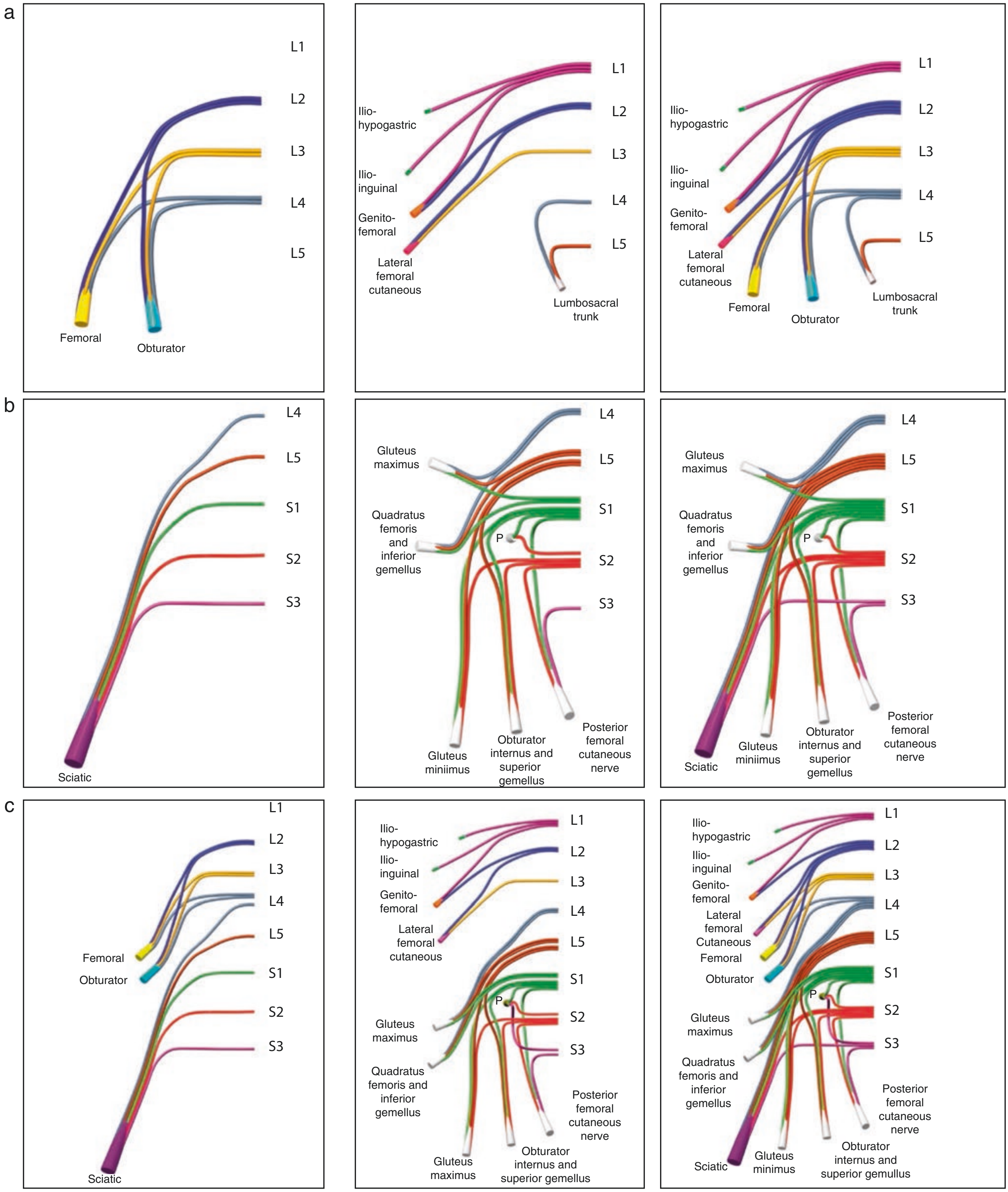
Figure LP6. MRI scans through the lumbar plexus.



1- Right external oblique and transverse muscles
2- Rectus abdominis muscles
3- Sacral promontory
4- Left common iliac artery
5- Left psoas major muscle
6- Left colon
7- Caecum
8- Right iliacus muscle
9- Right gluteus medius muscle
10- Wing of ilium
11- Right gluteus maximus muscle
12- Right 5th lumbar nerve and branches of the plexus
13- Right 1st sacral nerve
14- Erector spinae muscles
15- Sacrum
16- Left lumbar plexus
17- Left common iliac vein

Figure LP7. MRI scans through the lumbosacral plexus.

The Lumbosacral Plexus


a
L1
L2
L3
L4
L5
Femoral
Obturator
Ilio-
hypogastric
Ilio-
inguinal
Genito-
femoral
Lateral
femoral
cutaneous
L1
L2
L3
L4
L5
Lumbosacral
trunk
Ilio-
hypogastric
Ilio-
inguinal
Genito-
femoral
Lateral
femoral
cutaneous
Femoral
Obturator
Lumbosacral
trunk
L1
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L4
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b
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S1
S2
S3
Sciatic
Gluteus
maximus
Quadratus
femoris
and
inferior
gemellus
P
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S3
Gluteus
miniimus
Obturator
internus and
superior
gemellus
Posterior
femoral
cutaneous
nerve
Gluteus
maximus
Quadratus
femoris
and
inferior
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S3
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Gluteus
miniimus
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S3
Femoral
Obturator
Sciatic
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hypogastric
Ilio-
inguinal
Genito-
femoral
Lateral
femoral
cutaneous
L1
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L3
L4
L5
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S2
S3
P
Gluteus
maximus
Quadratus
femoris and
inferior
gemellus
Posterior
femoral
cutaneous
nerve
Gluteus
maximus
Obturator
internus and
superior gemellus
Ilio-
hypogastric
Ilio-
inguinal
Genito-
femoral
Lateral
femoral
Cutaneous
Femoral
Obturator
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L2
L3
L4
L5
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S3
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Gluteus
maximus
Quadratus
femoris and
inferior
gemellus
Posterior
femoral
cutaneous
nerve
Sciatic
Gluteus
minimus
Obturator
internus and
superior gemullus

Figure LP8. (**a**) Lumbar plexus, (**b**) sacral plexus, (**c**) lumbosacral plexus distribution.

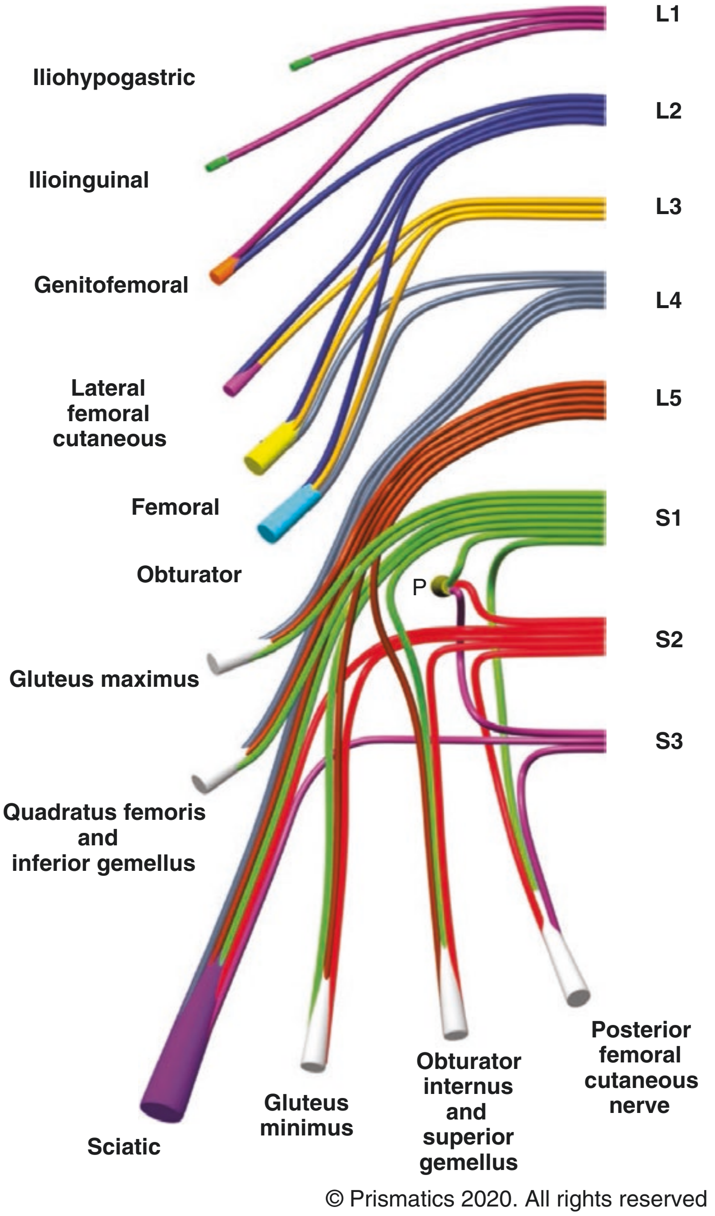
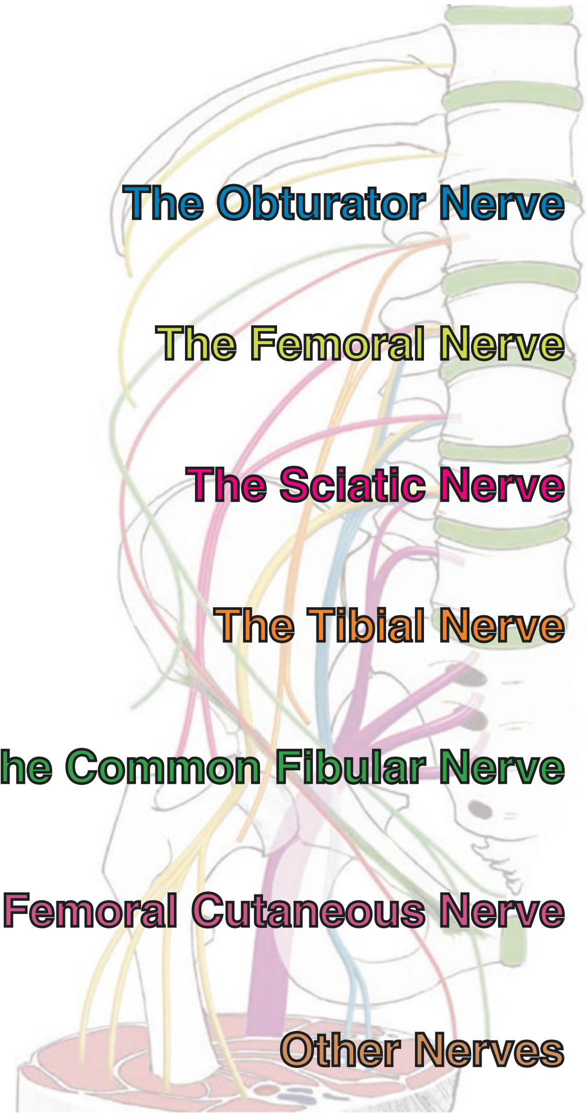

L1
Iliohypogastric
L2
Ilioinguinal
L3
Genitofemoral
L4
Lateral femoral cutaneous
L5
Femoral
S1
Obturator
P
Gluteus maximus
S2
S3
Quadratus femoris and inferior gemellus
Posterior femoral cutaneous nerve
Obturator internus and superior gemellus
Gluteus minimus
Sciatic

Figure LP9. Overview diagram of the lower limb plexus branches distribution.

PERIPHERAL BRANCHES



The Obturator Nerve

O

The Femoral Nerve

F

The Sciatic Nerve

Sc

The Tibial Nerve

T

The Common Fibular Nerve

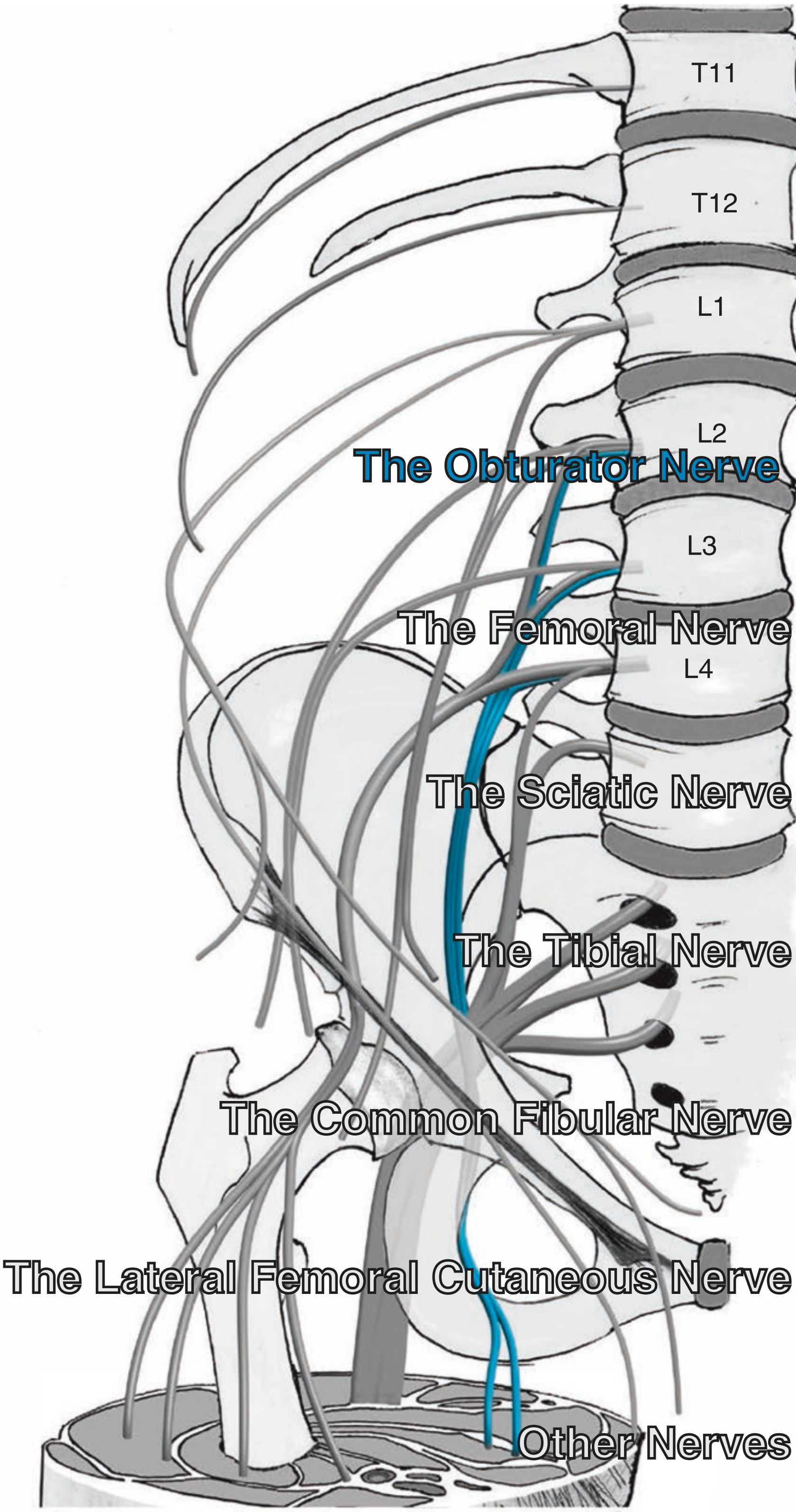
Fi

The Lateral Femoral Cutaneous Nerve

CLc

Other Nerves

IH
II


T11
T12
L1
L2
The Obturator Nerve
L3
The Femoral Nerve
L4
The Sciatic Nerve
The Tibial Nerve
The Common Fibular Nerve
The Lateral Femoral Cutaneous Nerve
Other Nerves

The Obturator Nerve

Morphological Data

The obturator nerve is a mixed nerve and the terminal branch of the lumbar plexus (Figures O1 and O2). Its function relates to the motor and sensitive innervation of the medial compartment of the thigh.

Origin

The obturator nerve comes from the L2, L3 and L4 roots of the lumbar plexus. It originates in the anterior branches of its constituting ventral lumbar roots. The posterior branches of these roots give off the femoral nerve.

The obturator nerve enters the lesser pelvis area from the medial face of the iliopsoas muscle whilst going outwards of and along the internal iliac vessels (Figures O3 and O4). It appears at the level of the L5 vertebra (Figure O3). It then faces the femoral nerve that goes laterally and alongside the iliopsoas muscle.

An inconstant extra branch can start in the L3 and L4 lumbar roots, after the origin of the obturator nerve: the accessory obturator nerve. It is situated laterally related to the obturator but also emerges from the medial face of the iliopsoas muscle.

It then goes down vertically and can end in several ways:

- Either with a terminal anastomosis with the femoral nerve or the obturator nerve
- Or with a terminal fan-shaped ramification that includes cutaneous branches for the upper part of the femoral triangle, muscular branches for the pectineus and adductor brevis muscle and a vascular branch and joint fibres for the hip joint capsule.

Path

After passing through the medial face of the iliopsoas muscle, the obturator nerve goes down in front of the sacroiliac joint (Figure O3). At this level, it faces the vas deferens or ovarian fossa medially (Figure O4).

It then goes further, in contact with the internal obturator muscle, and penetrates the thigh through a foramen at the level of the obturator membrane (Figure O3). This membrane separates the obturator internus muscle behind (situated in the pelvis minor) and the obturator externus muscle in front (situated at the top of the thigh).

The obturator nerve then divides into anterior and posterior branches (Figure O2). The muscle bundles of the adductor brevis, innervated by this nerve, are often found in between these branches.

Neurovascular Relations

In front of the sacroiliac joint, the obturator nerve faces (Figure O4):

- The ascending lumbar artery medially.
- The common iliac artery's termination and the origin of the external iliac artery, when the vascular fork is high, in front.

It is situated in the upper thigh (Figures O5, O6, O7, O8, O10, O11, O12, O13 and O14):

- Behind the pectineus muscle
- Below the inguinal ligament
- In front of the obturator externus muscle

The terminal branches of the obturator muscles face the medial circumflex femoral artery medially. This artery makes a loop with a medial convexity, close to the nerve.

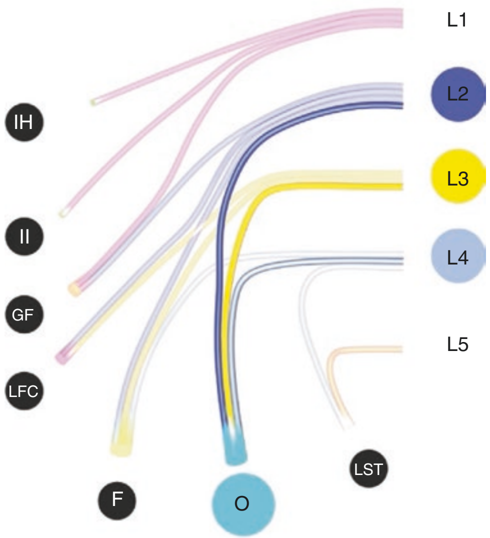


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Figure O1. Origin of the obturator nerve.

Electronic Supplementary Material The online version of this chapter (https://doi.org/10.1007/978-3-030-49179-6_13) contains supplementary material, which is available to authorized users.

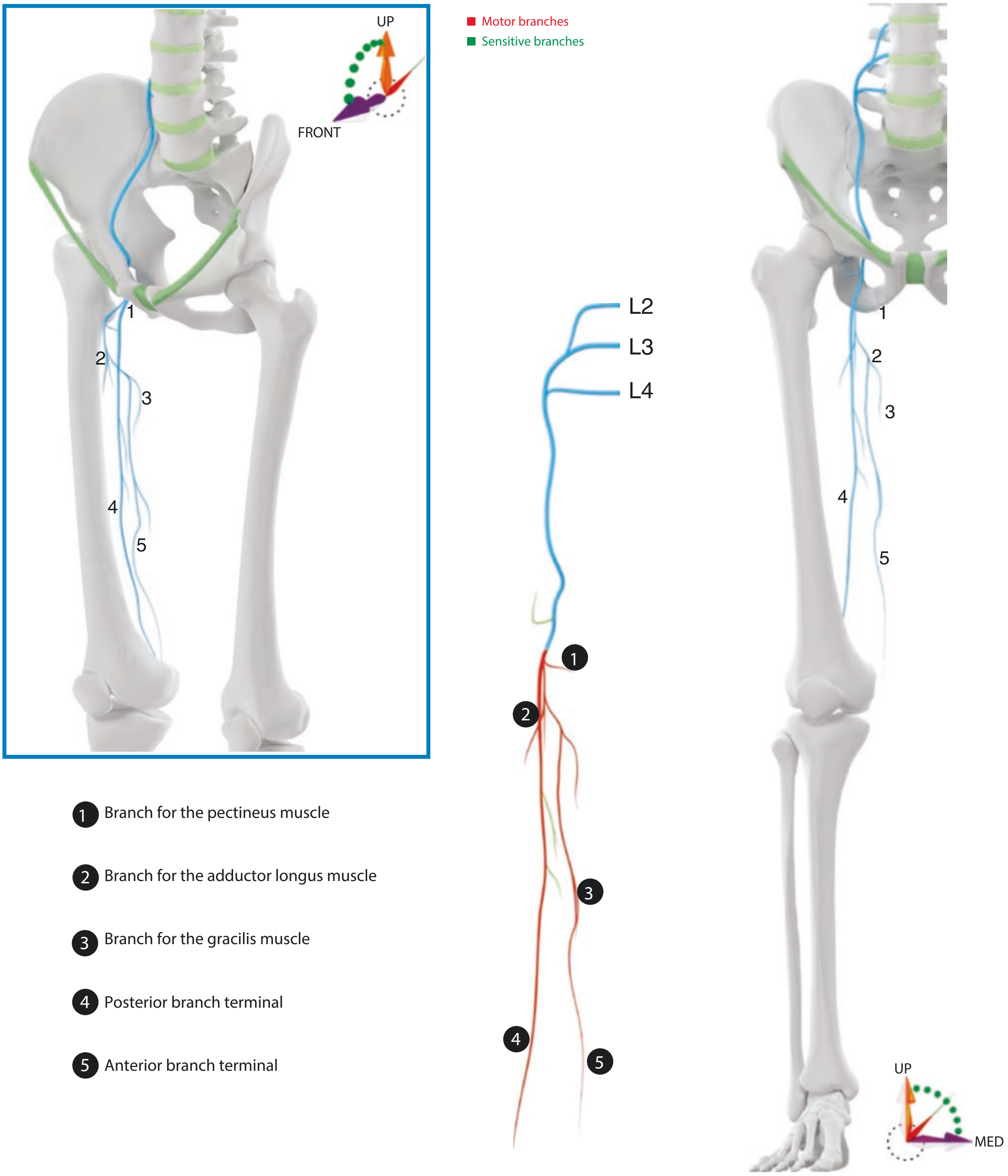
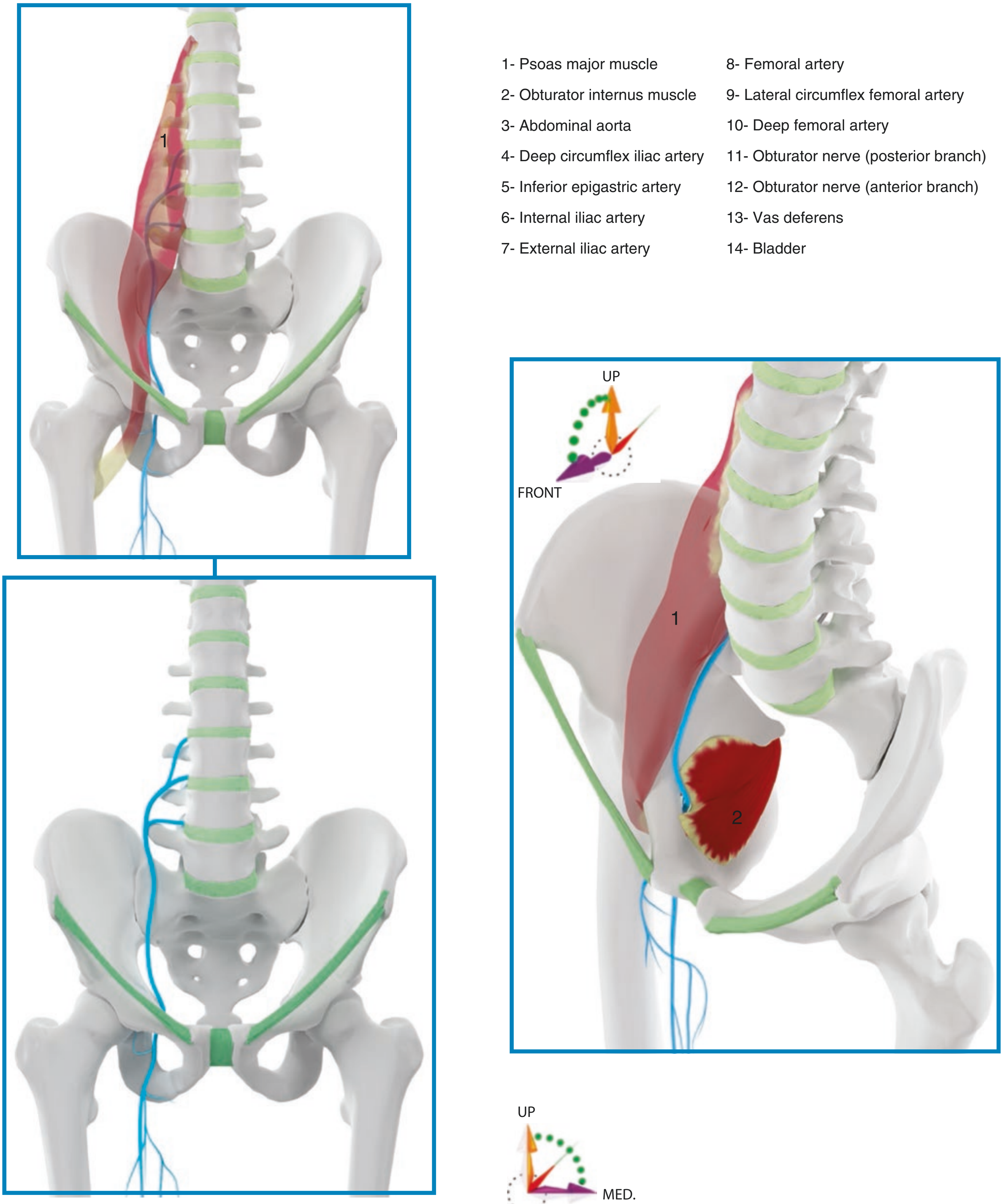

UP
FRONT
1
2
3
4
5
🟥 Motor branches
🟩 Sensitive branches
L2
L3
L4
①
②
③
④
⑤
UP
MED
① Branch for the pectineus muscle
② Branch for the adductor longus muscle
③ Branch for the gracilis muscle
④ Posterior branch terminal
⑤ Anterior branch terminal

Figure O2. Topographical distribution of the obturator nerve and its relations with bones.



1- Psoas major muscle
2- Obturator internus muscle
3- Abdominal aorta
4- Deep circumflex iliac artery
5- Inferior epigastric artery
6- Internal iliac artery
7- External iliac artery
8- Femoral artery
9- Lateral circumflex femoral artery
10- Deep femoral artery
11- Obturator nerve (posterior branch)
12- Obturator nerve (anterior branch)
13- Vas deferens
14- Bladder

Figure O3. Origin of the obturator nerve and its relations with muscles during its path in the pelvis.

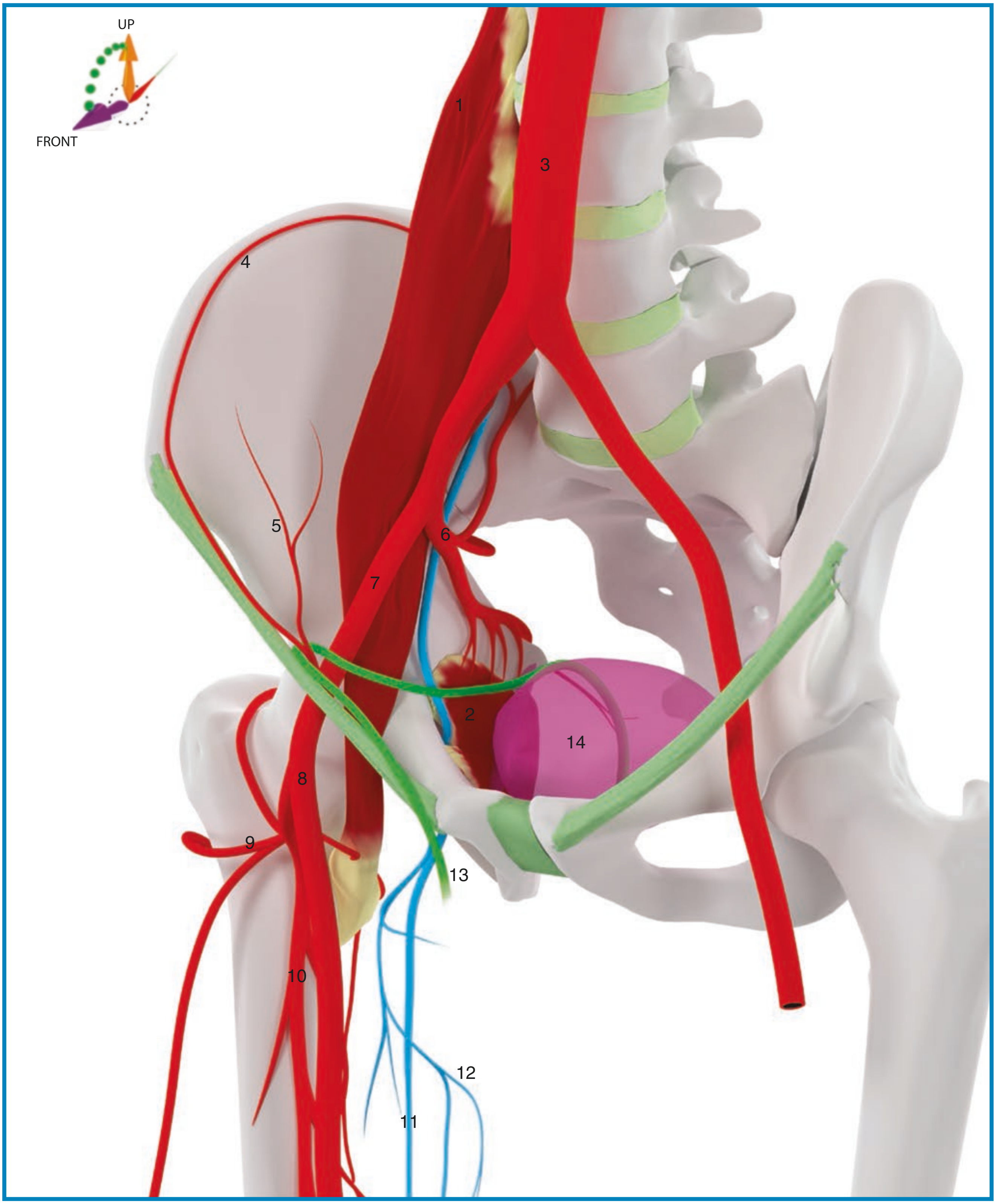

UP
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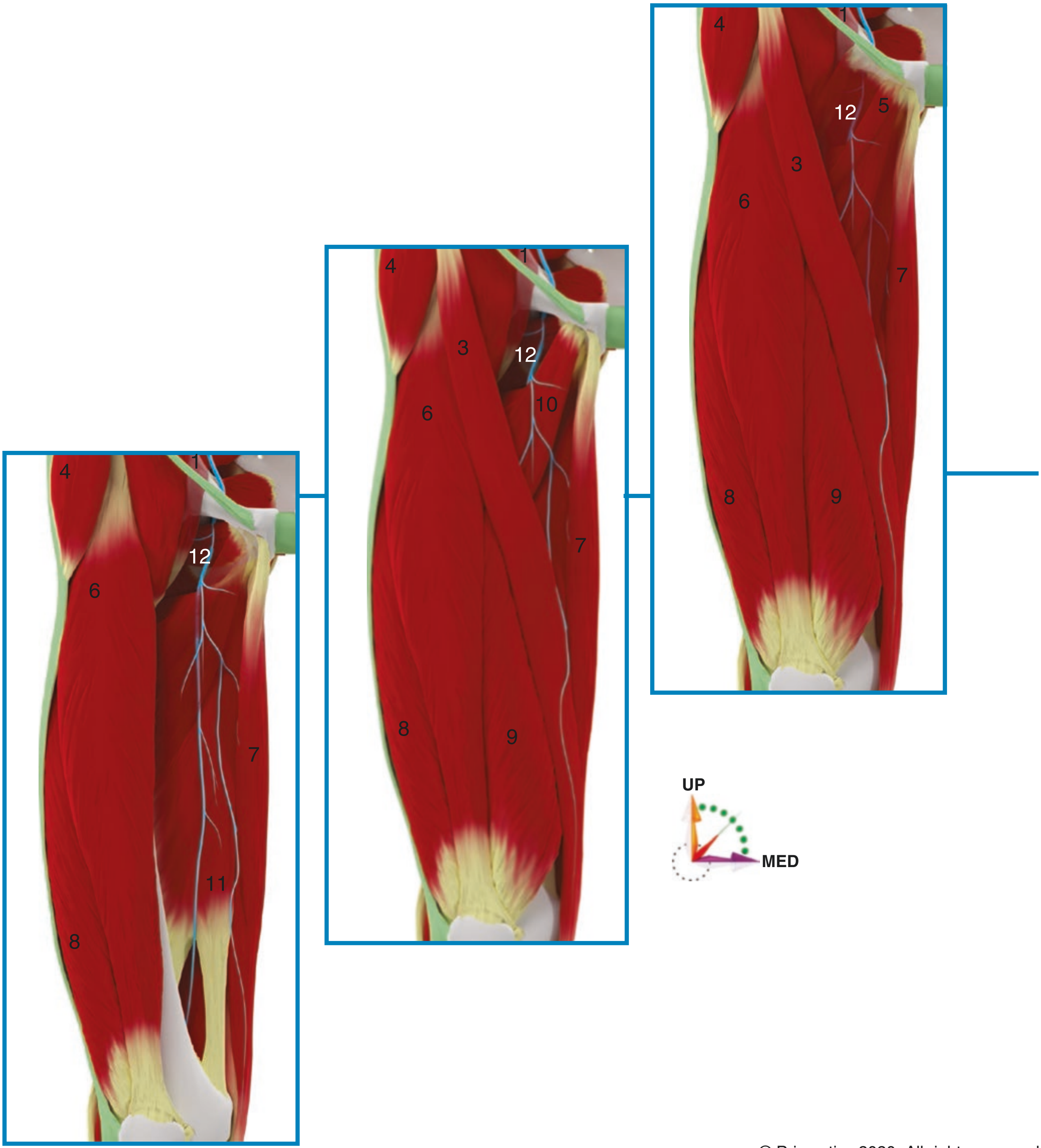
Figure O4. Vascular relations of the obturator nerve in the pelvis.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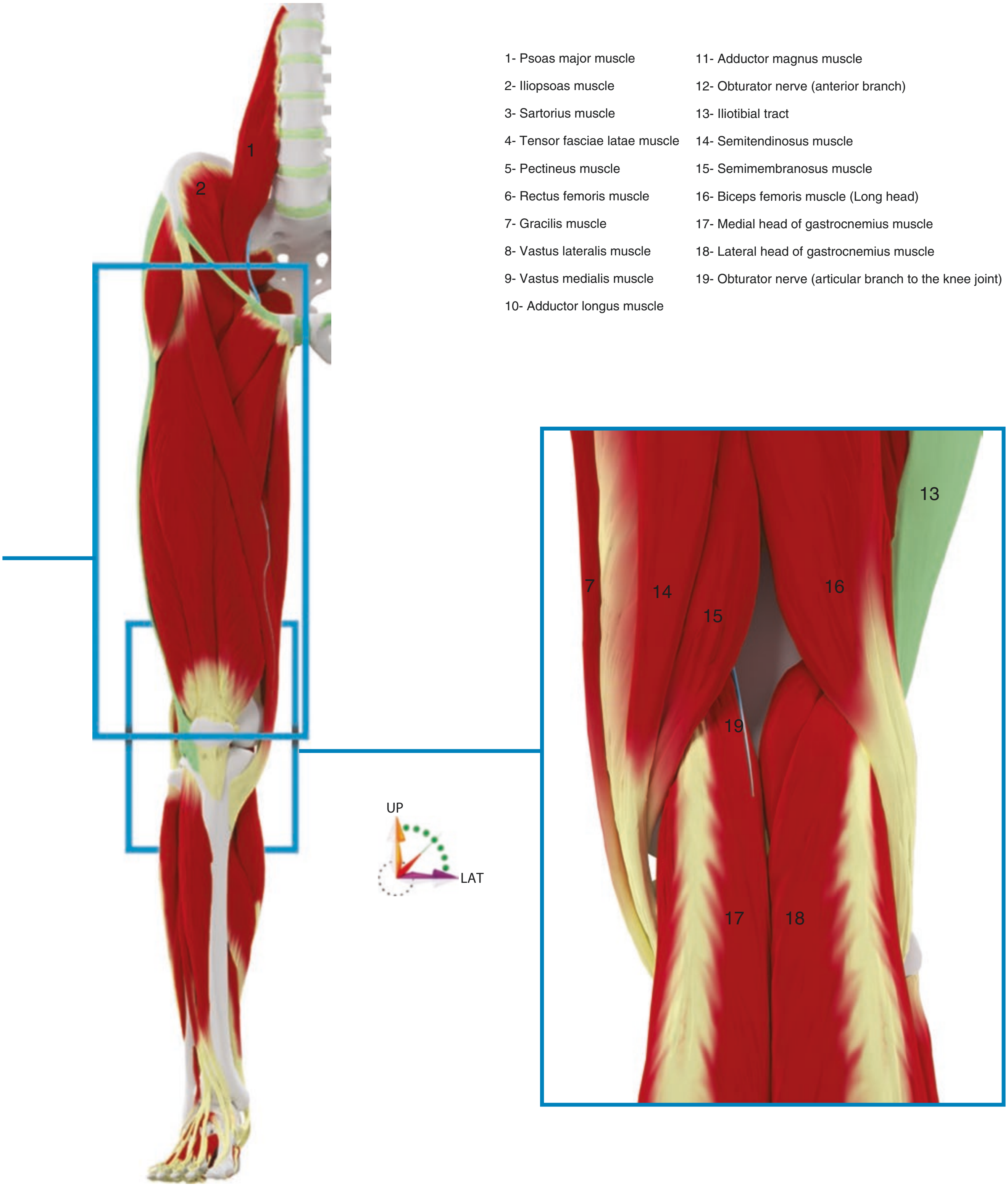
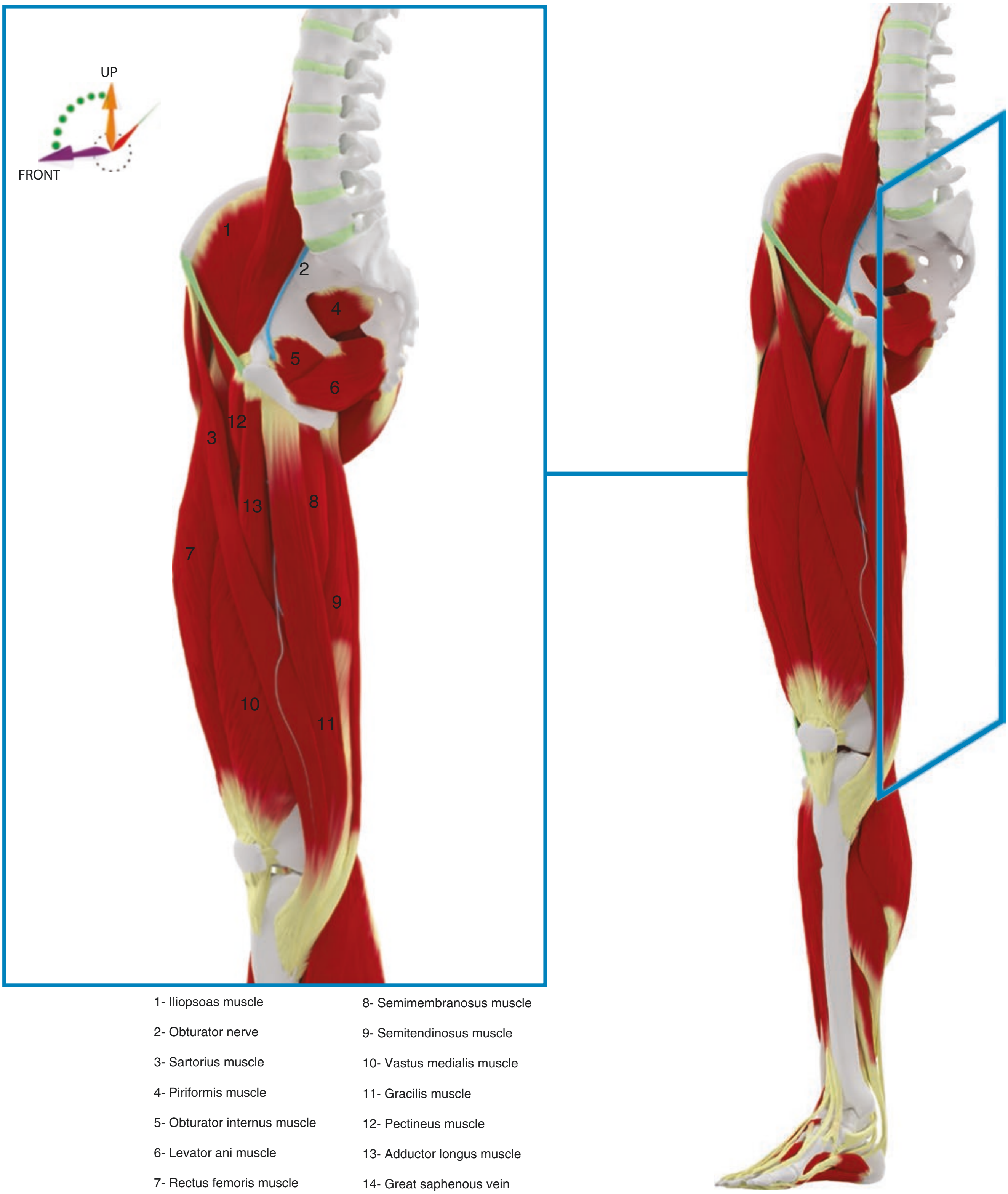
MED

Figure O5. Muscular relations of the obturator nerve in the thigh (anterior view from superficial to deep).



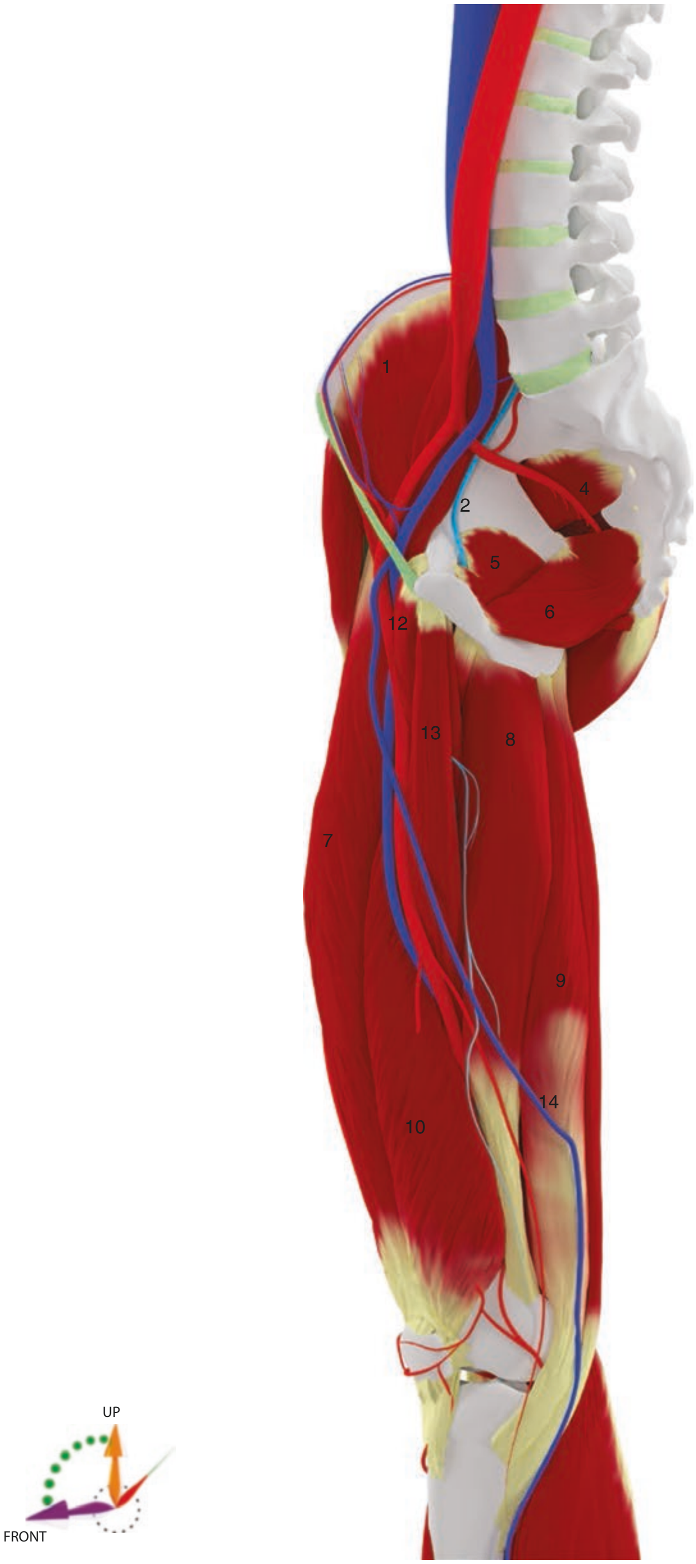
1- Psoas major muscle
2- Iliopsoas muscle
3- Sartorius muscle
4- Tensor fasciae latae muscle
5- Pectineus muscle
6- Rectus femoris muscle
7- Gracilis muscle
8- Vastus lateralis muscle
9- Vastus medialis muscle
10- Adductor longus muscle
11- Adductor magnus muscle
12- Obturator nerve (anterior branch)
13- Iliotibial tract
14- Semitendinosus muscle
15- Semimembranosus muscle
16- Biceps femoris muscle (Long head)
17- Medial head of gastrocnemius muscle
18- Lateral head of gastrocnemius muscle
19- Obturator nerve (articular branch to the knee joint)

Figure O6. Posterior view of the terminal branch of the obturator nerve in the popliteal fossa.



1- Iliopsoas muscle
2- Obturator nerve
3- Sartorius muscle
4- Piriformis muscle
5- Obturator internus muscle
6- Levator ani muscle
7- Rectus femoris muscle
8- Semimembranosus muscle
9- Semitendinosus muscle
10- Vastus medialis muscle
11- Gracilis muscle
12- Pectineus muscle
13- Adductor longus muscle
14- Great saphenous vein

Figure O7. Medial view of the thigh showing the muscular relations of the obturator nerve terminal branches.


1
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UP
FRONT

Figure O8. Medial view of the thigh showing the vascular relations of the terminal branches of the obturator nerve.

Collateral Branches

The collateral branches arise in the obturator foramen:

- Two articular nerves for the hip joint, in its anterior medial part.
- One to two nerves for the obturator externus muscle. The nerve of the obturator externus muscle generally divides into two branches, the upper and anterior parts of the muscle (Figures O5 and O7).

Terminal Branches

The anterior branch goes down along the pectineus and adductor longus muscles, lying firstly on the obturator externus muscle, and then the adductor brevis muscle. It ends in ramifications that innervate the skin of the internal face of the thigh and the adductor longus, pectineus and gracilis muscles and sometimes the adductor brevis (Figures O5 and O7).

The posterior branch begins its path between the pectineus muscle in front and the obturator externus muscle behind and then it sinks and goes through the obturator externus—innervated by that same posterior branch—in order to finally rest on the adductor brevis a little deeper. It then goes in front of the adductor magnus, also innervated by the posterior branch.

Motor Function

The obturator nerve innervates all of the adductor muscles of the thigh and the obturator externus muscle, thanks to a collateral branch. It is therefore in charge of the adduction and lateral rotation of the thigh (Figures O9 and O10).

Sensitive Function

The obturator nerve innervates the medial face of the thigh.

Anastomoses

It makes anastomoses with the femoral nerve through the saphenous nerve and, when it exists, with the accessory obturator nerve (Figure O10).

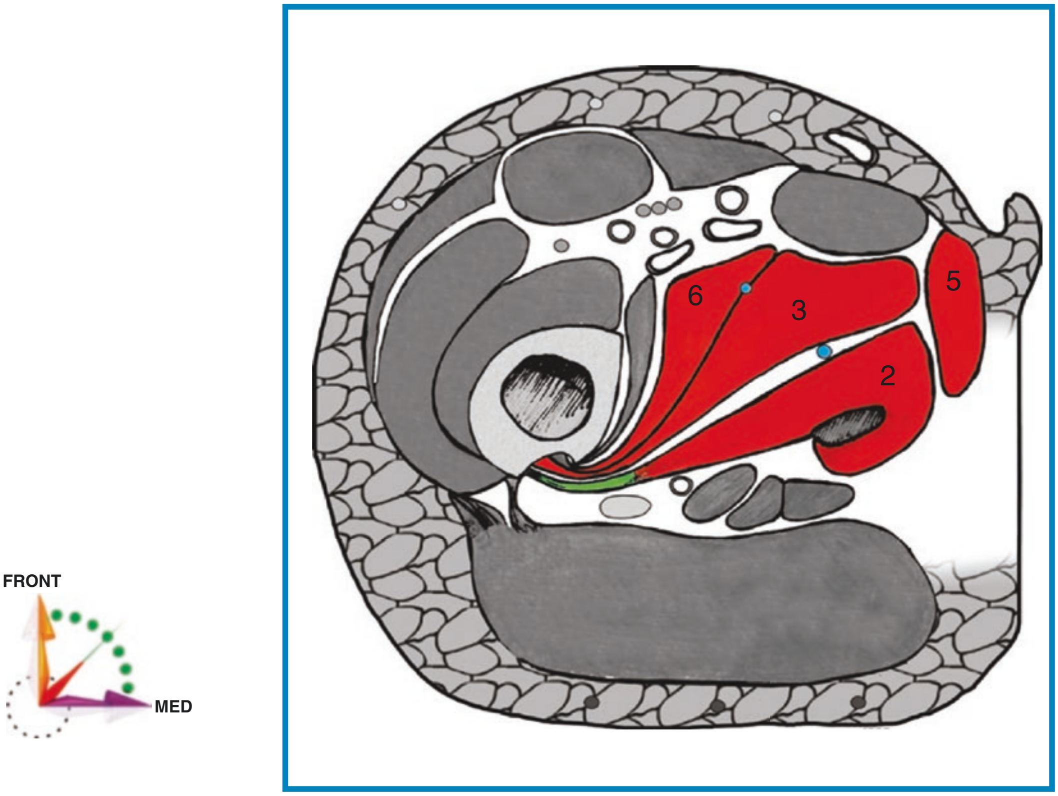
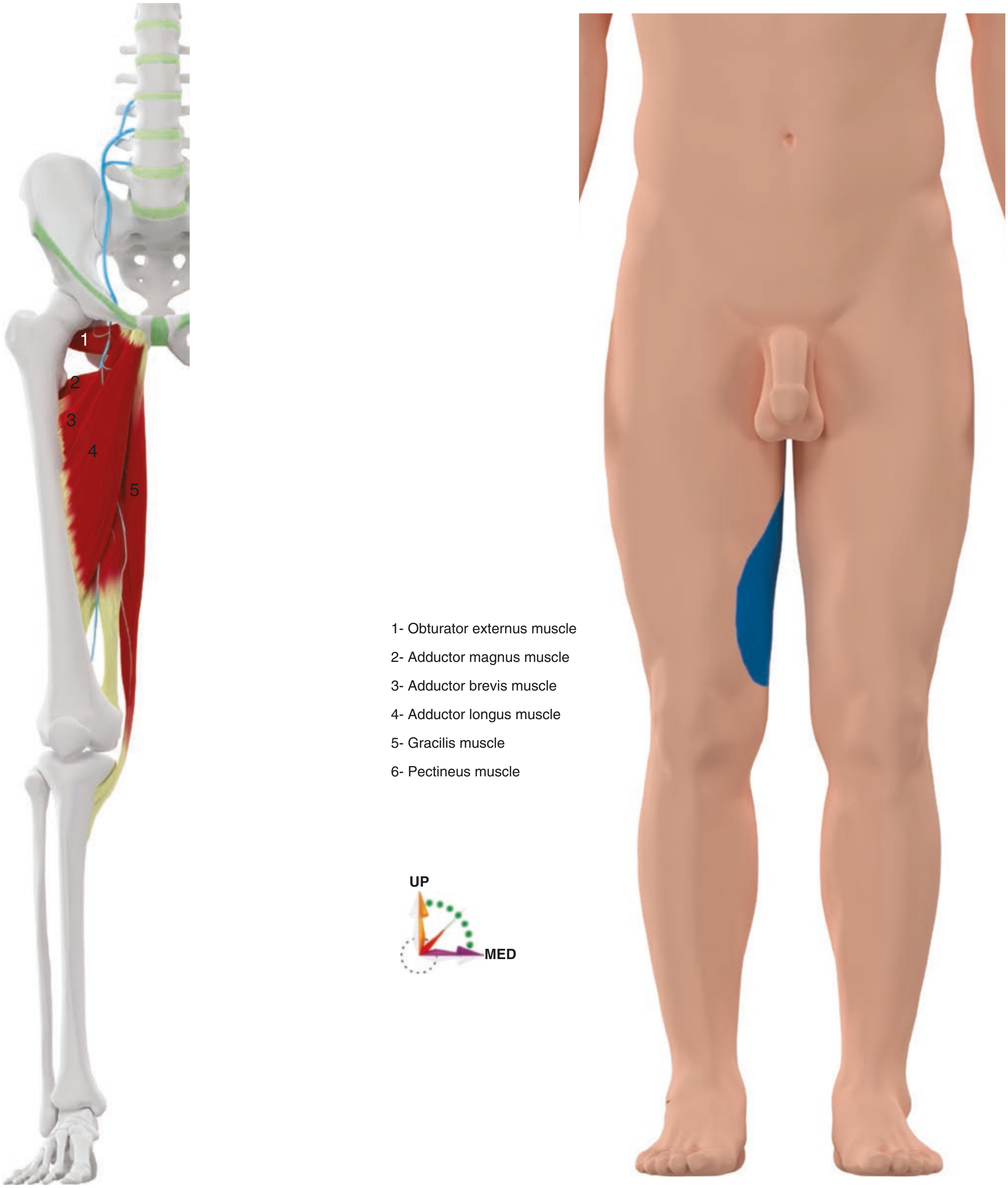
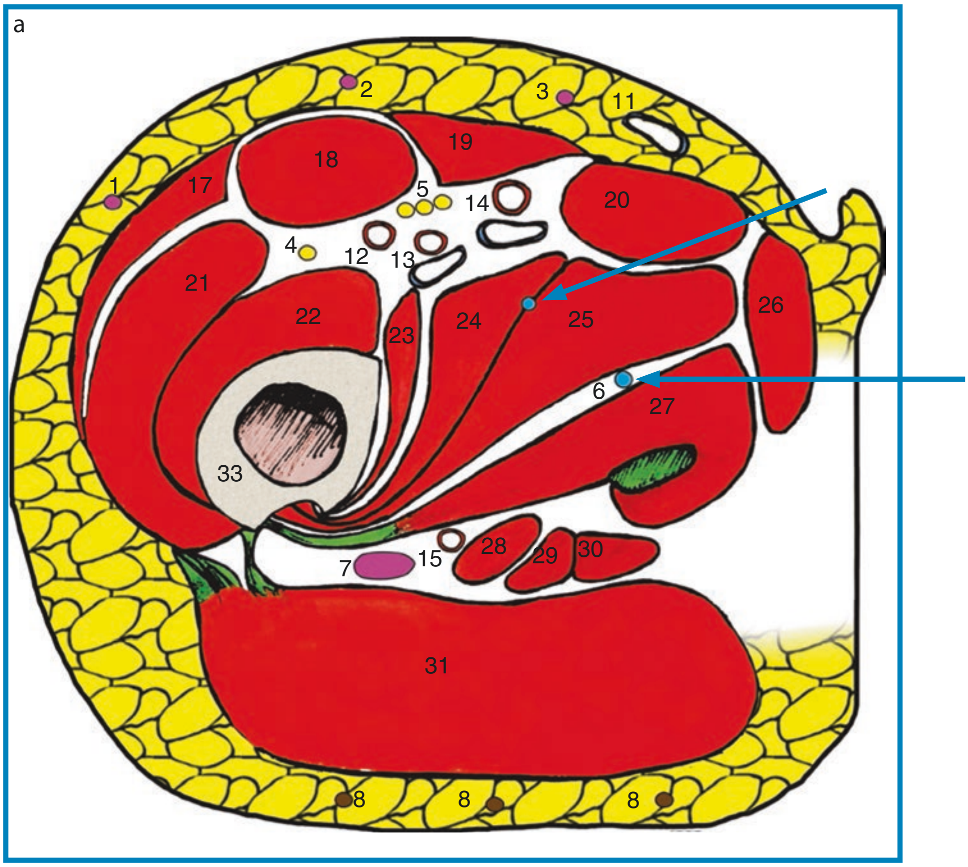


Figure O9. Motor innervation of the obturator nerve.



1- Obturator externus muscle
2- Adductor magnus muscle
3- Adductor brevis muscle
4- Adductor longus muscle
5- Gracilis muscle
6- Pectineus muscle

Figure O10. Motor and sensitive innervation of the obturator nerve.



1- Lateral femoral cutaneous nerve
2- Anterior cutaneous nerve of the thigh
3- Medial cutaneous nerve of the thigh
4- Nerve to the quadriceps muscle
5- Terminal branch of the femoral nerve
6- Branch of the obturator nerve
7- Sciatic nerve
8- Inferior cluneal nerves
9- Saphenous nerve
10- Posterior femoral cutaneous nerve

11- Great saphenous vein
12- Artery to the quadriceps muscle
13- Deep femoral artery and vein
14- Femoral artery and vein
15- Inferior gluteal artery
16- Deep branch of the deep femoral artery
17- Tensor fasciae latae muscle
18- Rectus femoris muscle
19- Sartorius muscle

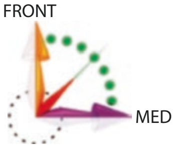
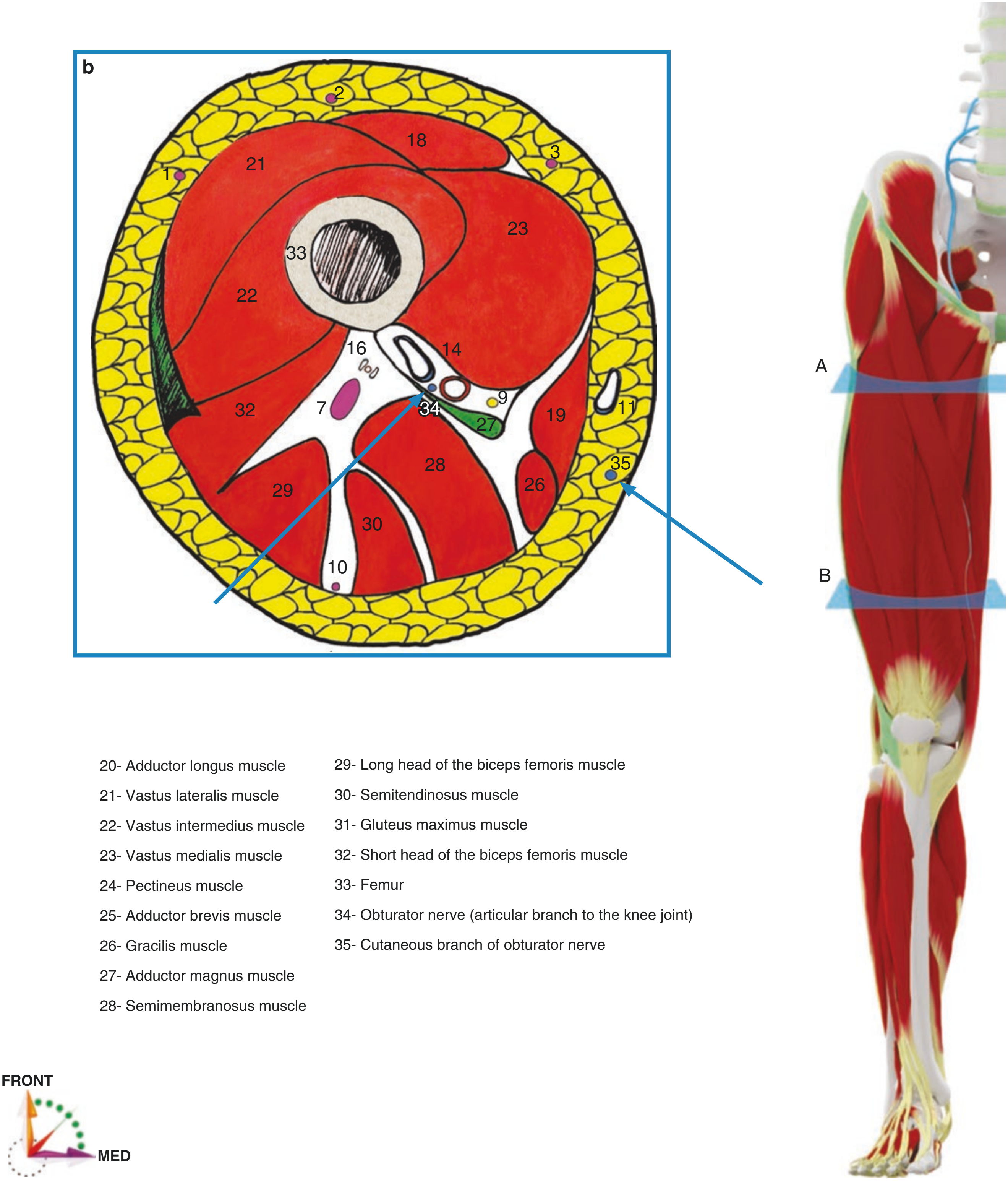
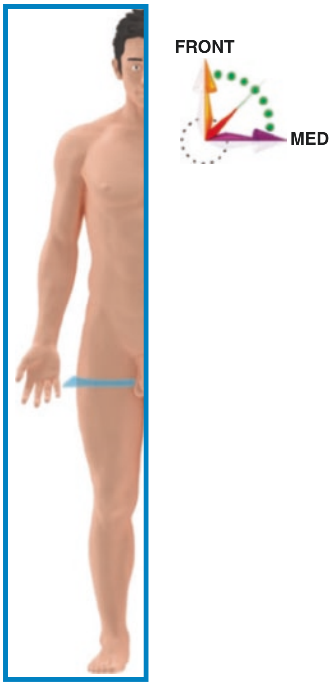


Figure O11. Relations of the obturator nerve in the thigh, axial view.



20- Adductor longus muscle
21- Vastus lateralis muscle
22- Vastus intermedius muscle
23- Vastus medialis muscle
24- Pectineus muscle
25- Adductor brevis muscle
26- Gracilis muscle
27- Adductor magnus muscle
28- Semimembranosus muscle
29- Long head of the biceps femoris muscle
30- Semitendinosus muscle
31- Gluteus maximus muscle
32- Short head of the biceps femoris muscle
33- Femur
34- Obturator nerve (articular branch to the knee joint)
35- Cutaneous branch of obturator nerve

Figure O12. Relations of the obturator nerve in the thigh, axial view.



1- Vastus lateralis muscle

2- Vastus intermedius muscle

3- Tensor fasciae latae muscle

4- Vastus medialis muscle

5- Rectus femoris muscle

6- Sartorius muscle

7- Femur

8- Femoral artery and vein

9- Femoral nerve

10- Deep femoral artery and vein

11- Adductor longus muscle

12- Gracilis muscle

13- Adductor brevis muscle

14- Adductor magnus muscle

15- Semimembranosus muscle

16- Sciatic nerve

17- Anterior branch of the obturator nerve

18- Posterior branch of the obturator nerve

19- Tendon of the biceps femoris muscle

20- Tendon of the semitendinosus muscle

21- Gluteus maximus muscle

22- Pectineus muscle

23- Lateral femoral cutaneous nerve

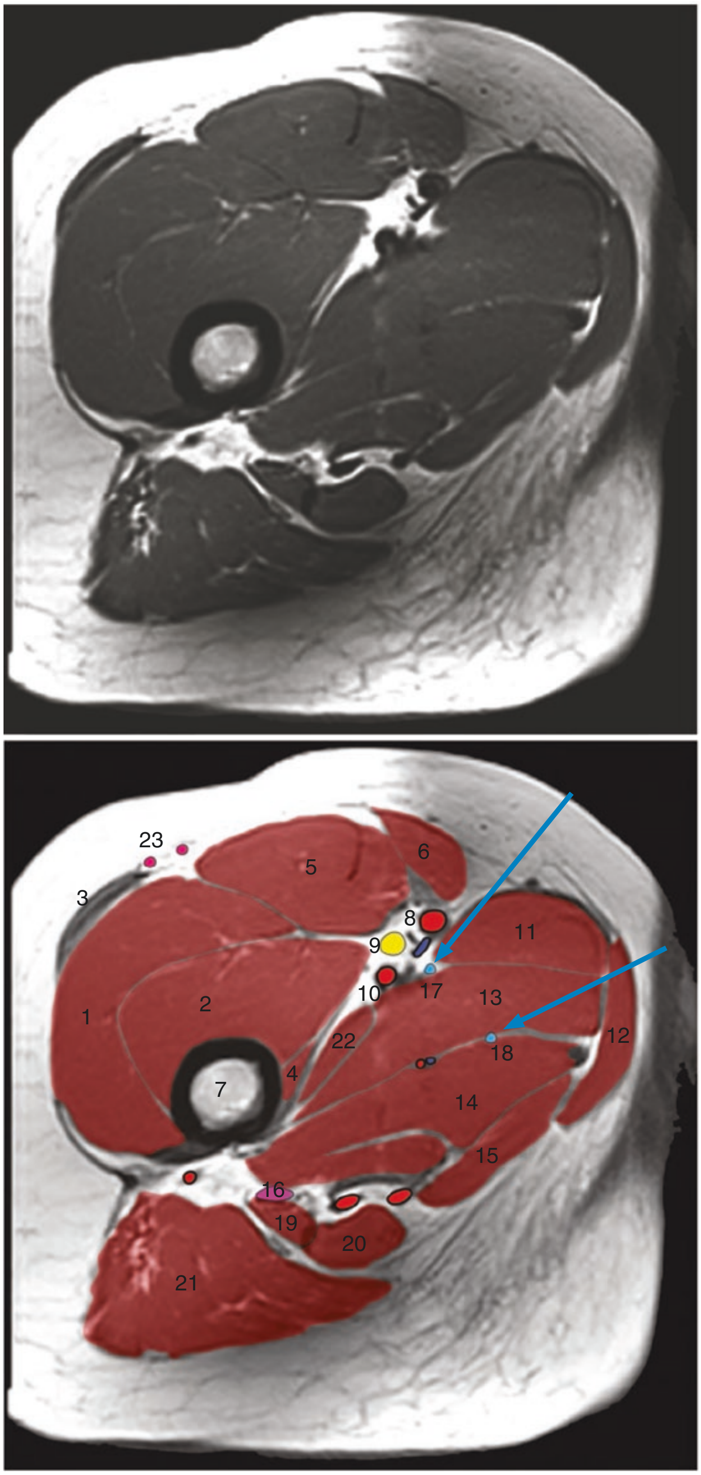
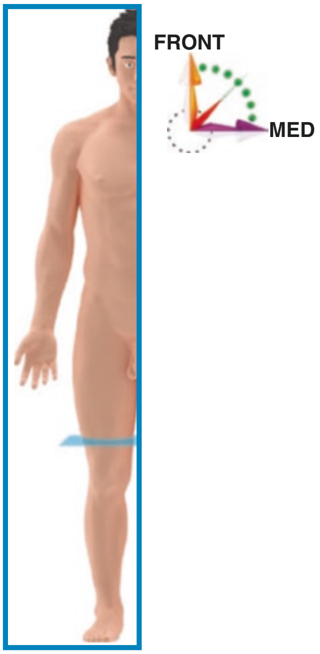


Figure O13. MRI scans at the proximal third of the thigh through the obturator nerve.



1- Vastus lateralis muscle
2- Vastus intermedius muscle
3- Rectus femoris muscle
4- Vastus medialis muscle
5- Femur
6- Short head of the biceps femoris muscle
7- Saphenous nerve
8- Femoral artery and vein
9- Perforating artery and vein of the deep femoral artery and vein
10- Common fibular nerve
11- Tibial nerve
12- Posterior femoral cutaneous nerve
13- Long head of the biceps femoris muscle
14- Adductor magnus muscle
15- Sartorius muscle
16- Gracilis muscle
17- Semimembranosus muscle
18- Semitendinosus muscle
19- Great saphenous vein
20- Obturator nerve (articular branch to the knee joint)
21- Obturator nerve (cutaneous branch)

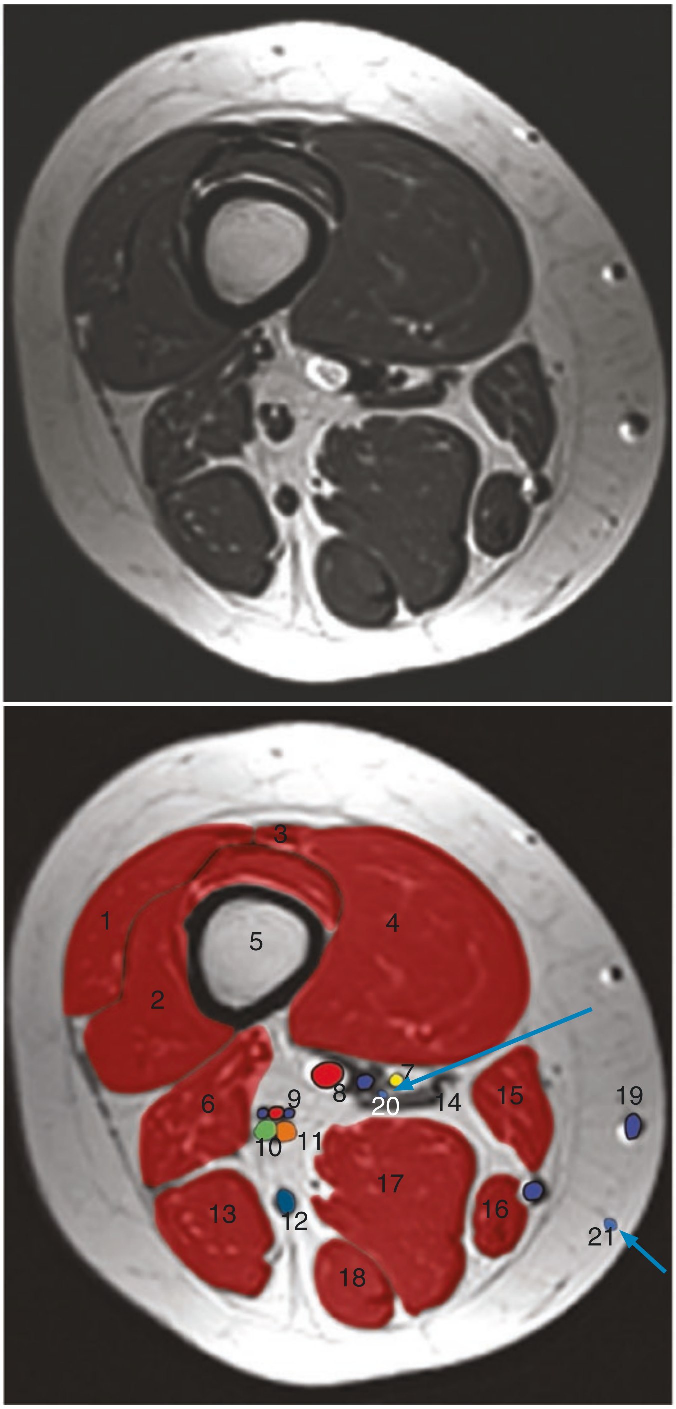


Figure O14. MRI scans at the distal third of the thigh through the obturator nerve.

Pathology

Obturator Neuralgia

The obturator nerve is a terminal branch of the lumbar plexus. It leaves the pelvis through the obturator canal, above the obturator membrane and the obturator externus muscle (Figure O3).

It is at this level that an entrapment neuropathy can occur (Figure O15). It innervates the adductor muscles of the thigh, the pectineus muscle and the gracilis muscle (Figure O10).

Aetiology

- Compression: This is the most frequent injury mechanism, responsible for a genuine entrapment neuropathy.
- Its trigger factors have been identified: pregnancy, intensive sport activity, etc. An obturator hernia should systematically be researched in case of suggestive clinical signs.
- Section or iatrogenic thermal injury: several types of surgeries can cause an iatrogenic obturator neuralgia: genito-urinary, orthopaedic, visceral, vascular, etc.

Clinical Significance

- Sensitive signs: The obturator nerve innervates the skin of the medial area of the thigh (Figure O10). The sensitive signs can be pain, hypoesthesia and paraesthesiae in this area. Sensitive signs only occur if the anterior branch is concerned and can appear only during effort: inguinal pain or at the level of the insertion of the adductor muscles that irradiates towards the internal face of the thigh and the posterior face of the knee. There can be a zone of hypoesthesia on the medial and inferior face of the thigh that only rarely goes beyond the knee. This pain can be relieved with flexion, a fact that differentiates it from hip injuries.
- Motor signs: motor signs only appear in severe injuries, or belatedly, walking difficulties with a feeling of instability in the leg, especially in athletes in jumping activities.

The obturator nerve is essentially in charge of the adduction of the thigh, which will be the first deficient function found in motor testing. During examination, a decrease in the capacity of adduction and medial rotation will be found, which ultimately leads to a disuse atrophy of the adductor muscles, causing the patient to walk with external rotation and circumduction.

Explorations

- An electrophysiology will have a paramount interest. It classically objectifies alterations of the speed of conduction of the nerve as well as signs of partial muscle denervation at the level of the adductors.
- An MRI of the thigh eliminates an extrinsic compression of the nerve.

Treatment

If the anterior branch is the only injured element and is diagnosed early, muscle stretching and electrical stimulation of the adductors can be suggested. Decompression surgery can be discussed if the compression is refractory after invasive management.

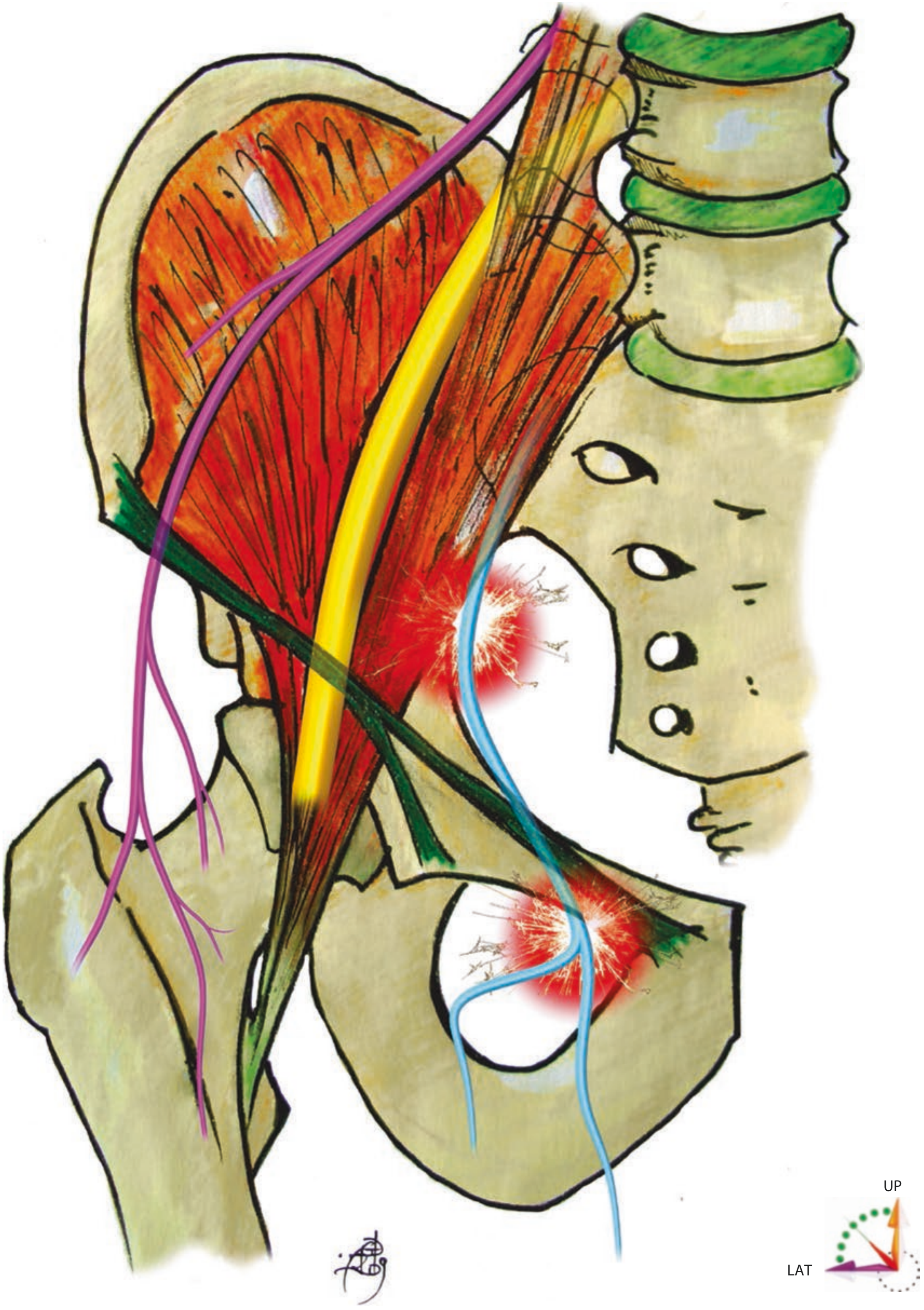


Figure O15. Pathology of the obturator nerve: potential sites of injury.

The Obturator Nerve

Morphological Data: Sono Anatomy

For the ultrasonographer, the path of the obturator nerve can be synthetically summarized as follows:

- It enters the thigh root through the medial and upper parts of the obturator foramen and divides into anterior and posterior branches.
- The anterior branch travels between the pectineus and adductor brevis muscles and then between the adductor longus and the adductor brevis muscles.
- The posterior branch is located between the adductor brevis and the adductor magnus muscles.
- The causes of its neuropathy will be described more extensively in the “Pathology” section, but emphasis should be placed on nerve compression, particularly in relation to a pelvic tumour.
- The other aetiologies responsible for obturative neuralgia are essentially iatrogenic, traumatic, post-obstetrical, collateral causes of obturative hernia or after highly intensive practice of sport. A case of idiopathic obturative neuralgia has been reported, by compression of the nerve in the closed foramen.

Installation

The patient is placed in a supine position, in external thigh rotation.

Equipment and Location

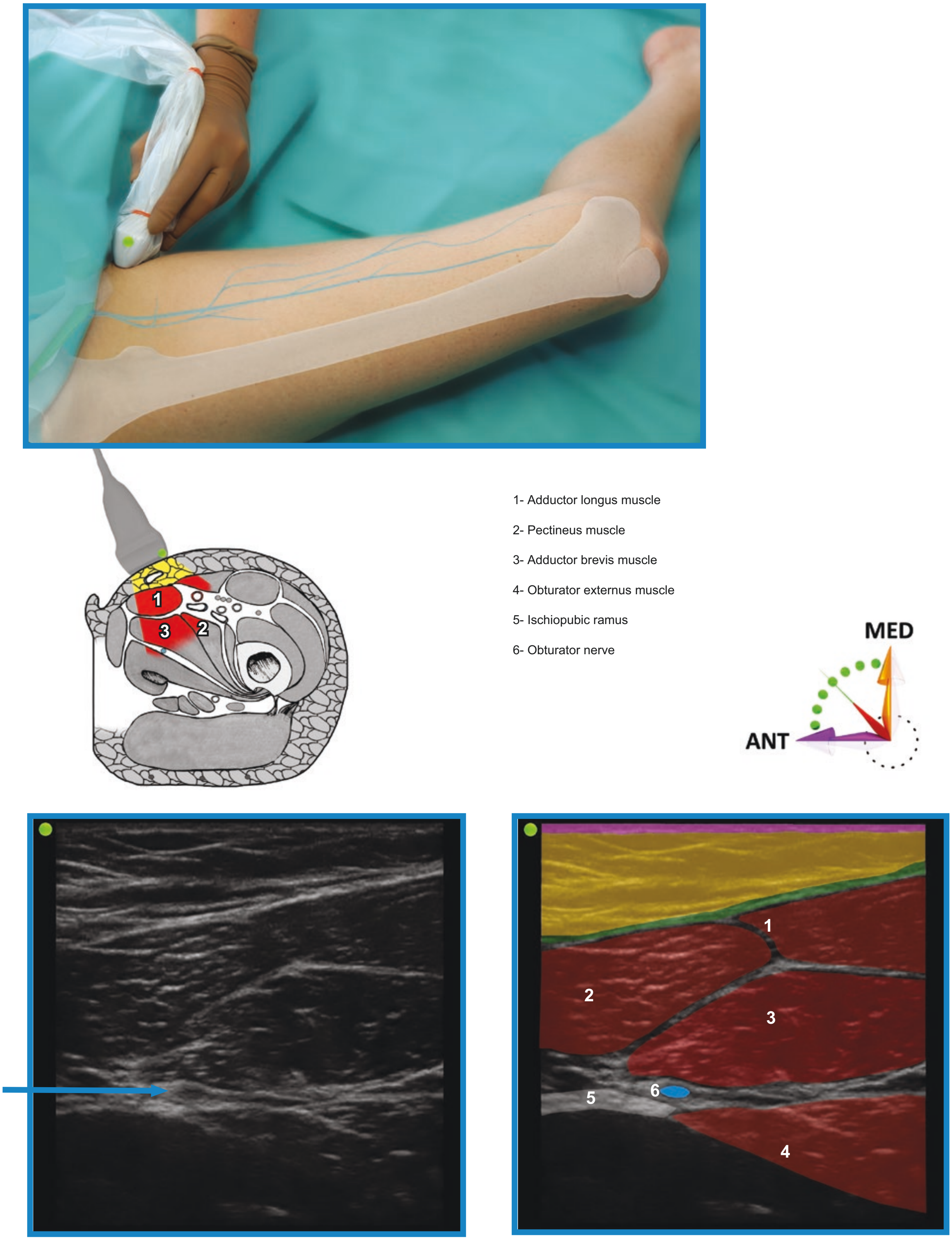
- Type of probe: linear, high frequency, or else, depending on weight, low-frequency probe.
- Probe axis: the probe is placed in the inguinal fold, in the transverse (axial) axis, slightly oblique caudally (bottom and inside) and medially so as to be fully positioned in the hip flexion fold.

Ultrasound Procedure

The probe is placed in the inguinal flexion fold. Initially positioned opposite the artery and femoral vein, it is slid first medially so as to render apparent pectineus muscle, and then medially, and the adductor longus and adductor brevis muscles are observed successively.

It is necessary to identify vascular structures using a coloured Doppler, searching for the great saphenous vein junction and the femoral vein, which must be left laterally to the probe. Marking is done with alternating pressure/decompression movements of the probe. The obturator nerve is found deep, which requires appropriate adjustment of the ultrasound scanner; initial depth of field can be immediately adjusted to 6 cm, and then adapted secondarily.

At the exit of the closed foramen, the obturator nerve is placed behind the pectineus muscle and in front of the obturator externus muscle. Its branches of division emerge before gradually diverging, the anterior branch being placed between the pectineus and adductor brevis muscles and the posterior branch between the adductor brevis and adductor magnus muscles. Depending on the more or less cephalic inclination of the probe, remaining in the flexion fold, the two branches of the obturator nerve can be followed by cephalic translation to their point of convergence. Beyond this point, it is quite difficult to obtain a clear view of the trunk of the obturator nerve, upstream of its junction into terminal branches (Figures O16–O18).



1- Adductor longus muscle

2- Pectineus muscle

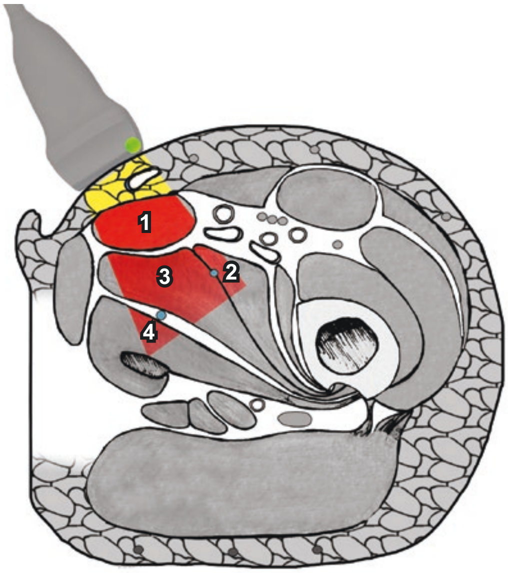
3- Adductor brevis muscle

4- Obturator externus muscle

5- Ischiopubic ramus

6- Obturator nerve

Figure O16. Ultrasound transversal views of the obturator nerve at the level of the obturator foramen.



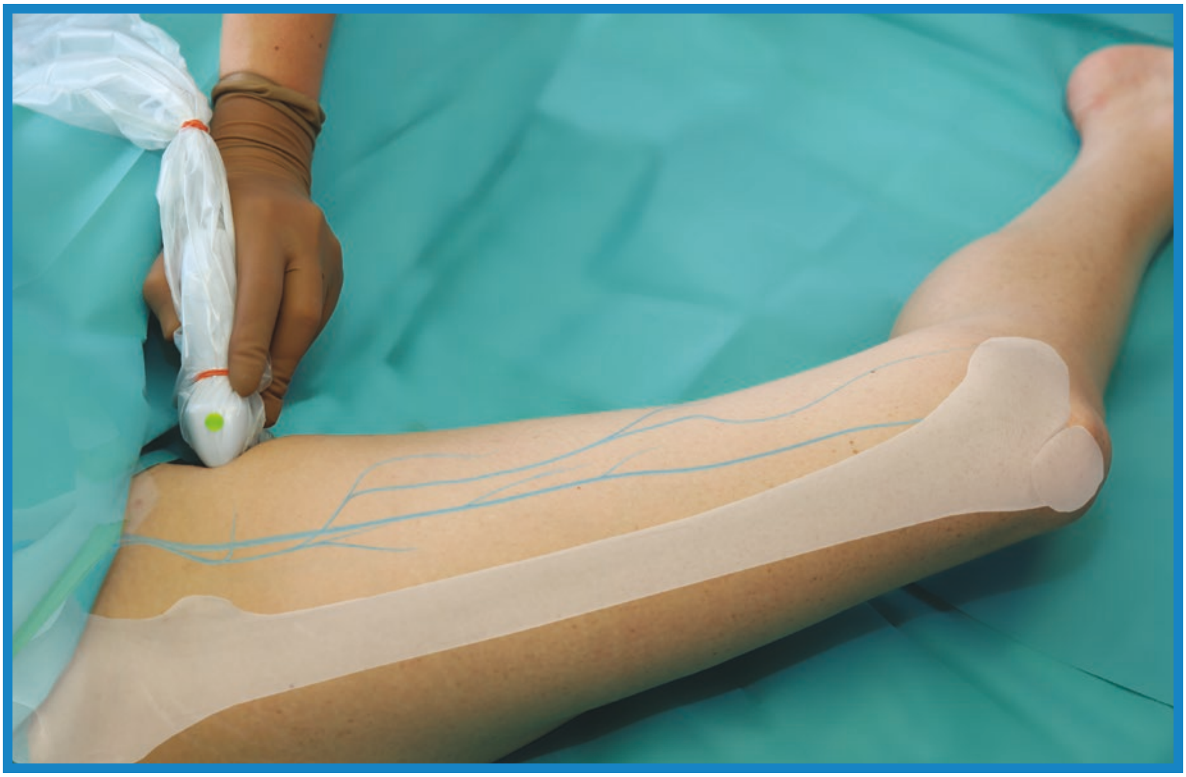
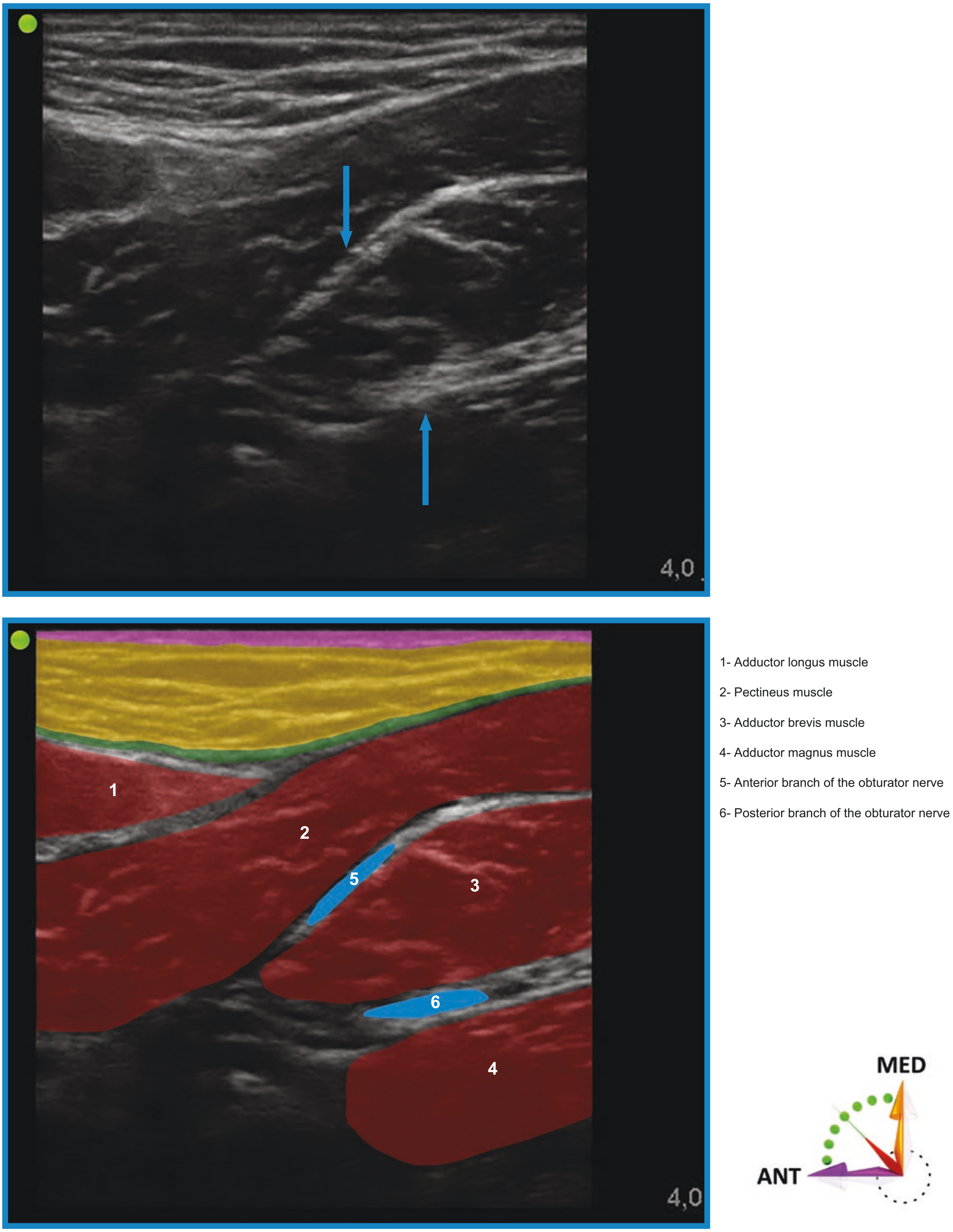


Figure O17. Ultrasound probe optimal positioning to visualize the obturator nerve at the proximal part of the thigh.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6
4
4,0
1- Adductor longus muscle
2- Pectineus muscle
3- Adductor brevis muscle
4- Adductor magnus muscle
5- Anterior branch of the obturator nerve
6- Posterior branch of the obturator nerve
MED
ANT

Figure O18. Ultrasound transversal views showing the anterior and posterior division at the proximal part of the thigh.

Interventional Procedure

Infiltration/Test Block

Indication

It is possible to propose the creation of an obturator block in case of major spasticity of the adductors, hindering daily hygiene care or access to the perineum, in multi-handicapped patients. If the test block is positive, toxin injections, nerve phenolization or obturator neurotomy can be discussed.

Nerve infiltration may also be indicated in the context of neuropathic pain in the territory of the cutaneous branch of the nerve on the inner, more distal surface of the thigh.

Technique

The "in plane" position of the probe facilitates ultrasound detection of the nerve and insertion of the infiltration needle. The block can be selective depending on whether it is intended for the anterior or posterior branch. It is possible to fetch the common trunk of the obturator nerve from the closed foramen and then the two branches as described above. Puncture is performed from side to side in medial, avoiding vascular structures thanks to the colour Doppler marking. Suction test before injection is the rule.

A complete block of the obturator nerve does not necessarily render is adduction impossible because the adductor muscles often receive cross innervation from the femoral nerve and the sciatic nerve (Figure O19).

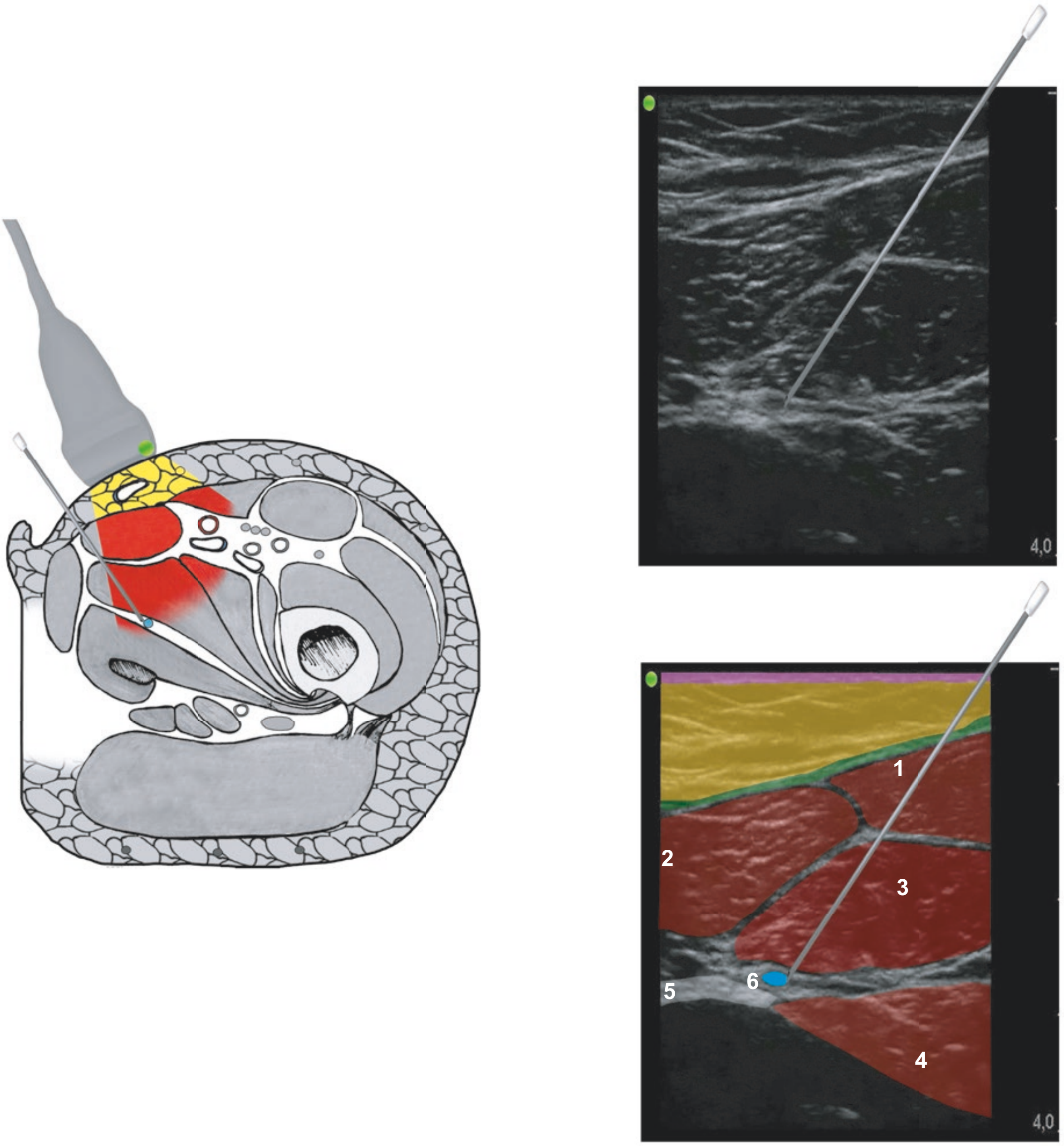
PNS

It is not recommended to perform peripheral nerve stimulation of the obturator nerve because the anatomical location of the nerve branches creates a high risk of mobilization of the lead, given the amplitudes of movements at this level. Generally speaking, the stimulation would be very positional in nature, resulting in an intensity of stimulation and perception that is highly variable and therefore uncomfortable. On the other hand, it is quite possible to stimulate the spinal ganglion of L2 or L3 to cover the same painful territory by means of root stimulation.

RFP

Pulsed radiofrequency of this nerve is a rare indication.

It is well-described in the reference attached to this chapter. The main recommendation concerning this procedure is to respect the motor branches as much as possible and therefore to address the nerve as distally as possible, in order to maintain the ratio of stimulated fibres to the number of total fibres in favour of the sensory quota.



1- Adductor longus muscle

2- Pectineus muscle

3- Adductor brevis muscle

4- Obturator externus muscle

5- Ischiopubic ramus

6- Obturator nerve

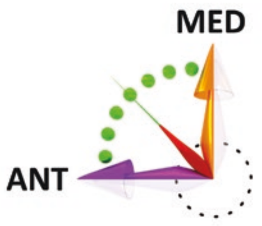


Figure O19. Anaesthetic block approach of the obturator nerve at the thigh level.

Surgical Procedure

Surgical Indications

Approach is necessary to perform a neurotomy of the obturator nerve. The purpose of this procedure is to reduce the spasticity of the hip adductor muscle. It is generally proposed in paraplegics to facilitate perineal hygiene and self-examination and in diplegic cerebral palsy, when there is shear stress in the lower limbs. It is preferable to more deeply respect the posterior branch to spare the stabilizing muscles of the hip.

Skin Incision

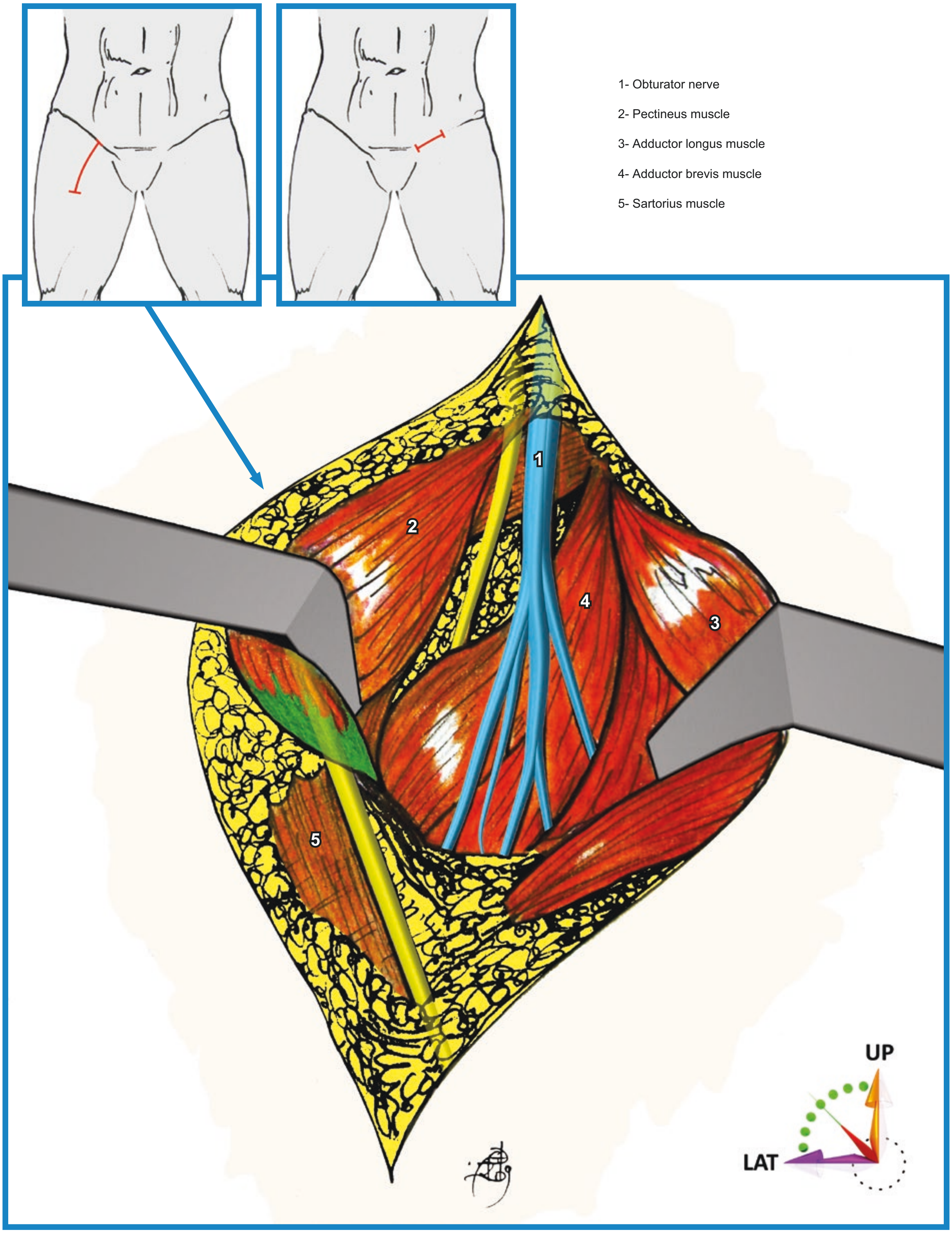
Some teams make a fairly vertical incision. Others prefer an incision at the groin fold, opposite the adductor longus insertion (Figure O20).

Nervous Exposure

Once the fascia is split between the adductor longus muscle inwards and the pectineus muscle outwards, the anterior branch of the obturator nerve, pressed against the adductor brevis muscle in the back, is exposed without difficulty. This approach is performed inside the sartorius muscle that can be found at the lower and lateral part of the incision, when it is vertical (Figures O21 and O22).

Technical Pitfalls

- Damage to femoral and/or iliac vessels
- Damage to the femoral nerve
- Peritoneal breach, in case of ascending first, ascending to the nervous trunk
- Abdominal hernia in case of failing closure



1- Obturator nerve

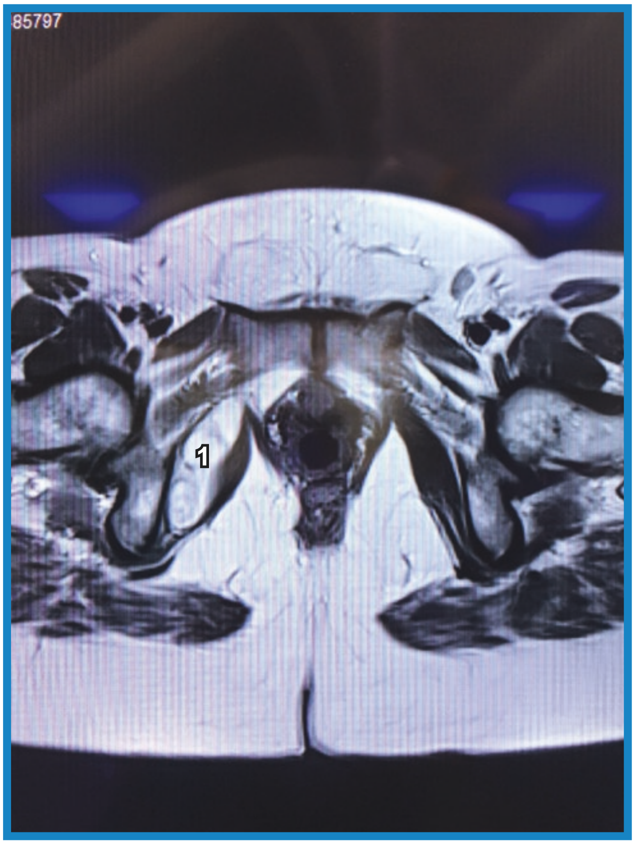
2- Pectineus muscle

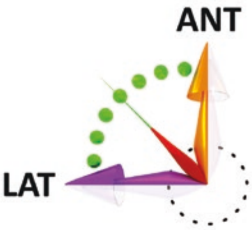
3- Adductor longus muscle

4- Adductor brevis muscle

5- Sartorius muscle

Figure O20. Surgical approach of the obturator nerve at the thigh level.





1-Obturator nerve neuroma

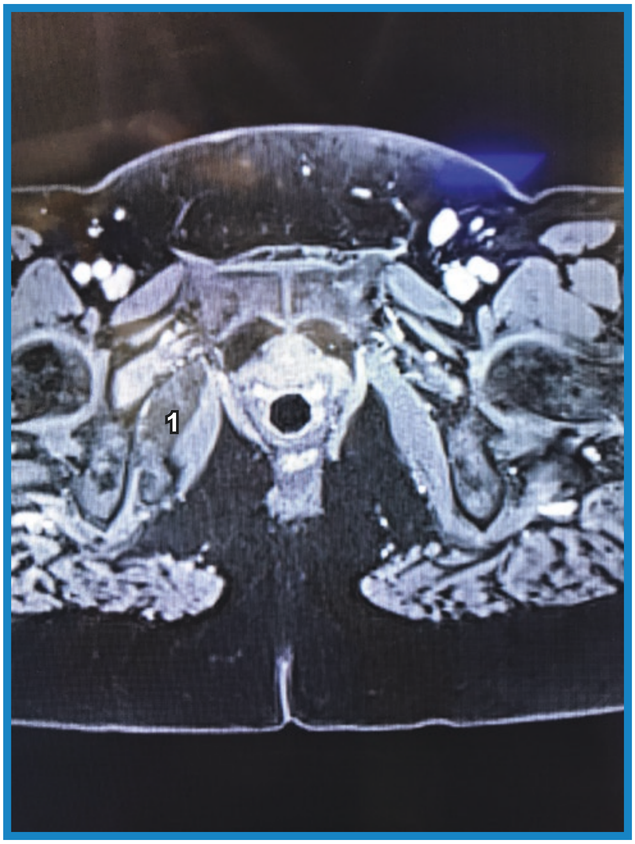
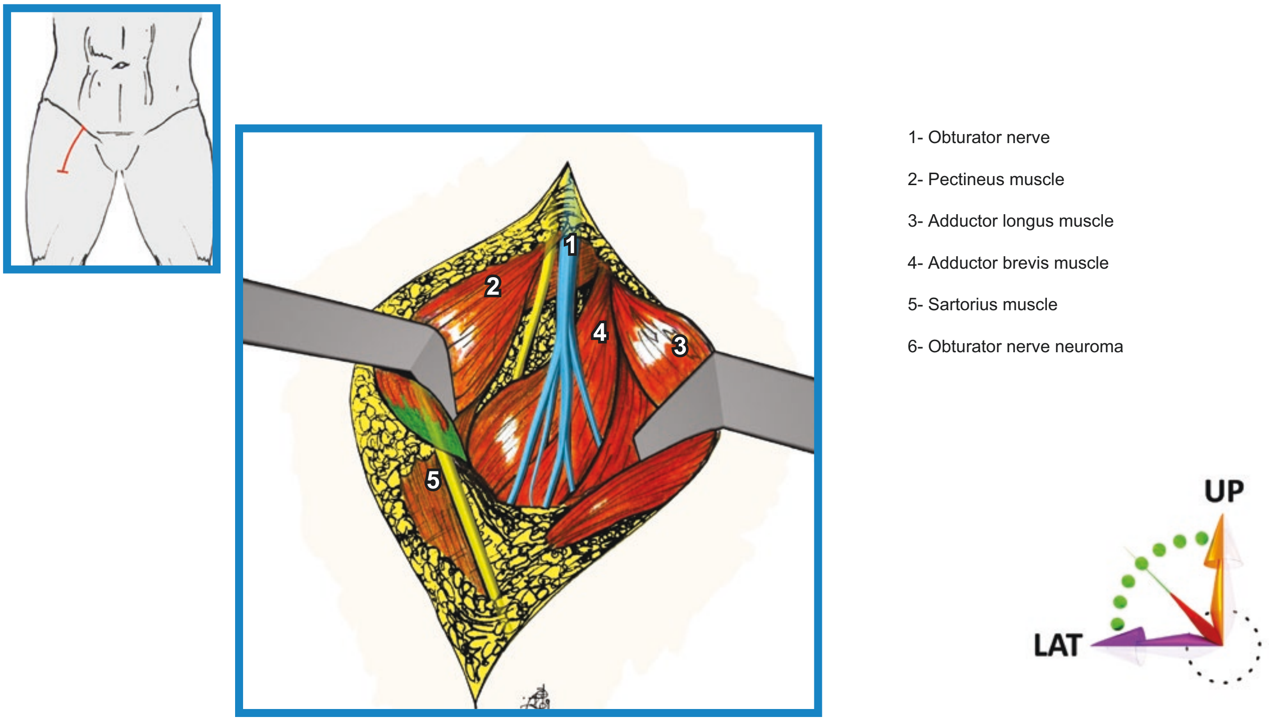


Figure O21. MRI axial views showing a voluminous neurinoma of the right obturator nerve.


1
2
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1- Obturator nerve
2- Pectineus muscle
3- Adductor longus muscle
4- Adductor brevis muscle
5- Sartorius muscle
6- Obturator nerve neuroma
UP
LAT

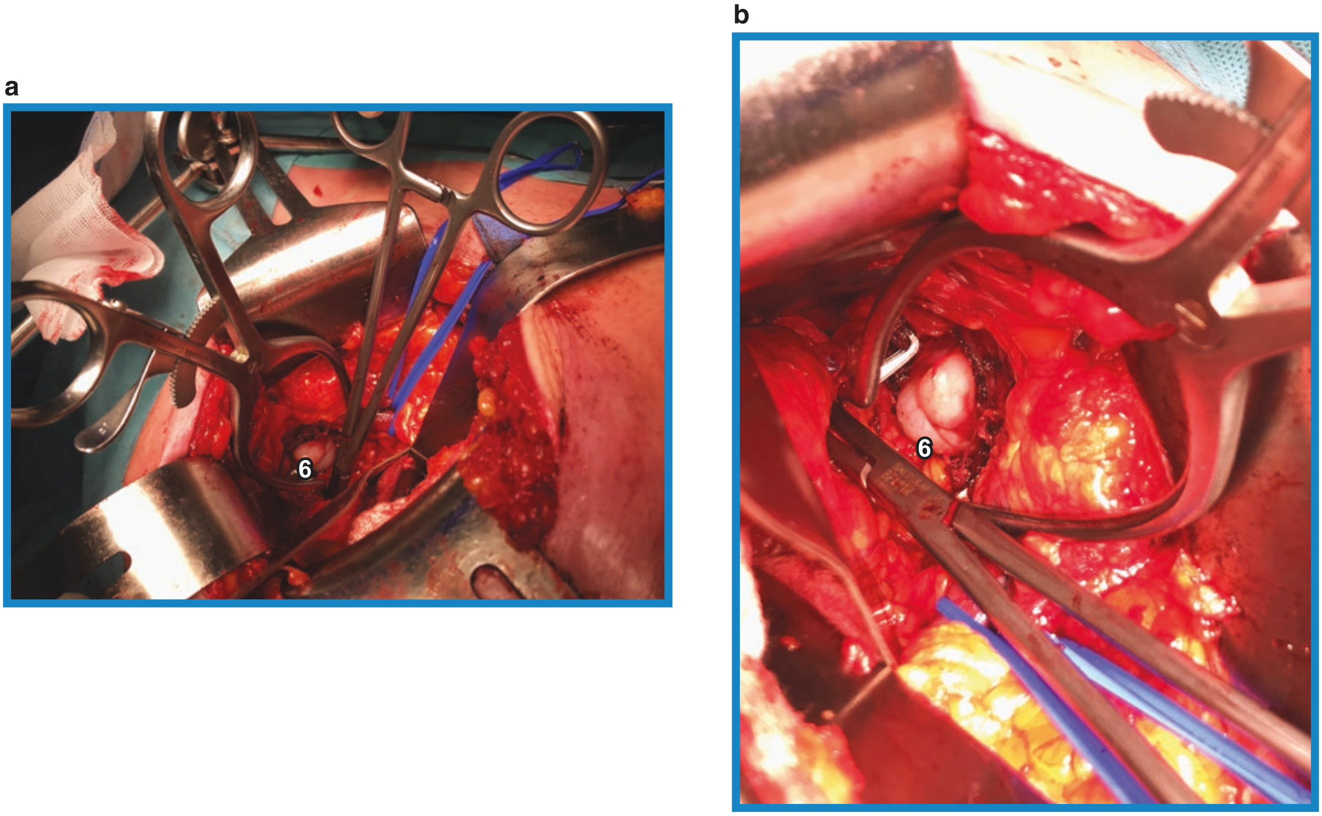
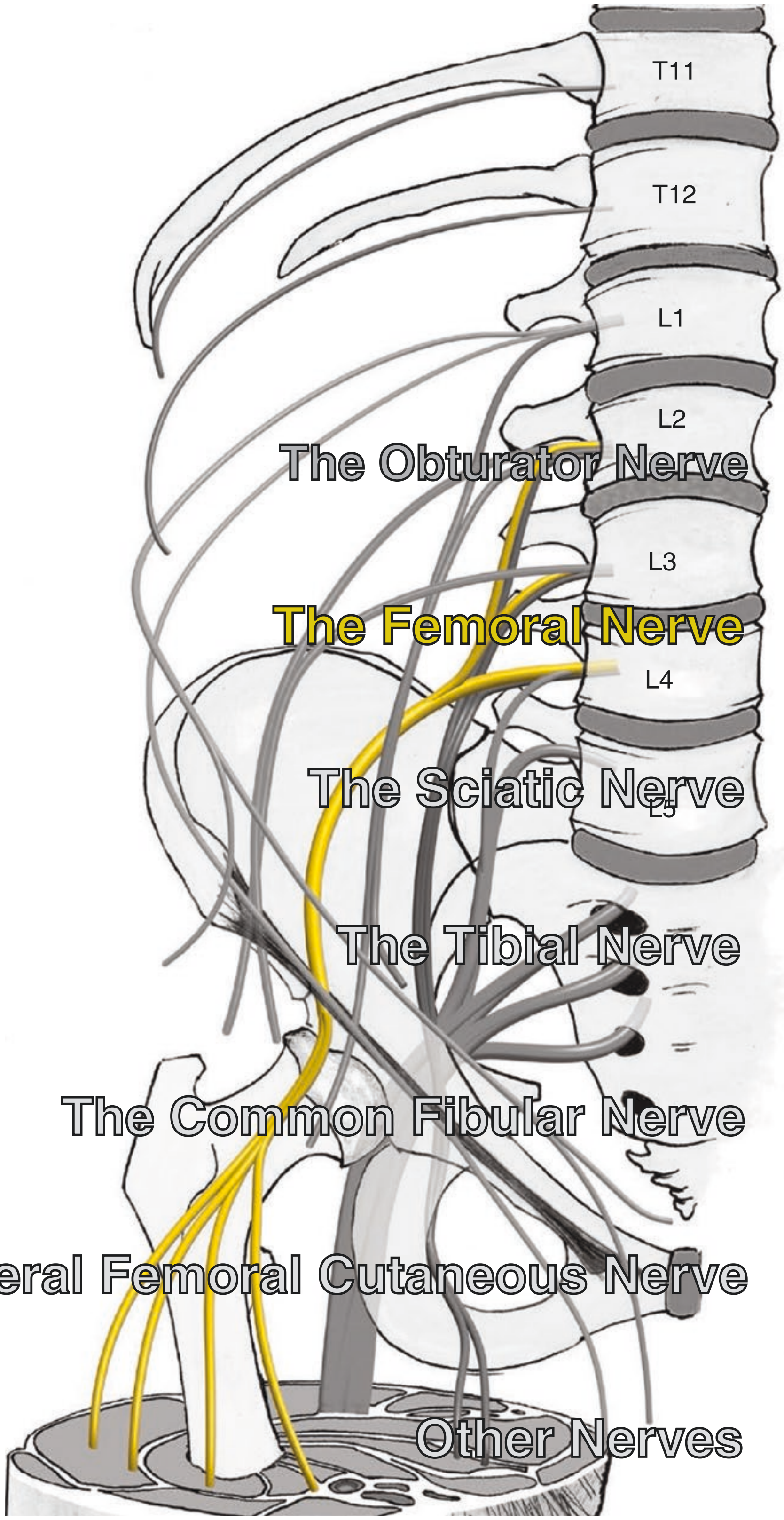


Figure O22. Surgical approach to the neurinoma of the obturator nerve. (**a**) Recline muscles allowing access to the neuroma. (**b**) Extraction of the neuroma.



The Obturator Nerve

The Femoral Nerve

The Sciatic Nerve

The Tibial Nerve

The Common Fibular Nerve

The Lateral Femoral Cutaneous Nerve

Other Nerves

The Femoral Nerve

Morphological Data

The femoral nerve is a mixed nerve. It is the main terminal branch of the lumbar plexus. Its main function is the innervation of the muscles of the anterior compartment of the thigh.

Origin

It is constituted of the roots of L2, L3 and L4 (Figures F1 and F2). The posterior branches of these lumbar roots unite when they go between the two layers of the iliopsoas muscle (Figure F3), under the lateral femoral cutaneous nerve and under and behind the obturator nerve.

Path

The femoral nerve goes between the psoas and iliac nerves and then reaches the top of the thigh (Figure F3).

At this level, it is situated under the iliac fascia and faces the caecum in front and to the right and the descending colon in front and to the left. It lies against the groove of the psoas muscle, under an aponeurotic membrane.

It then crosses the femoral canal (Figure F4) just outside of the projection at its middle, the iliopectineal arch, where it rests outside of the femoral artery (Figure F5).

In the femoral canal, it faces the femoral branch of the genitofemoral nerve and the femoral vascular pedicle medially (Figure F3).

Then, it divides into two main terminal branches: the anterior and posterior branches (Figures F2, F4, F5 and F6).

Neurovascular Relations

Under the iliac fascia, the femoral nerve faces the external iliac artery via the iliacus muscle medially.

Under the inguinal ligament, it faces the femoral artery medially via the iliopectineal arch (Figure F5).

At the same level, the lateral circumflex femoral artery, which is a collateral branch of the femoral artery, goes behind or through the terminal branches of the femoral nerve.

Collateral Branches

The femoral nerve successively gives rise to:
- Muscle branches for the iliopsoas and pectineus muscles
- A branch for the femoral artery

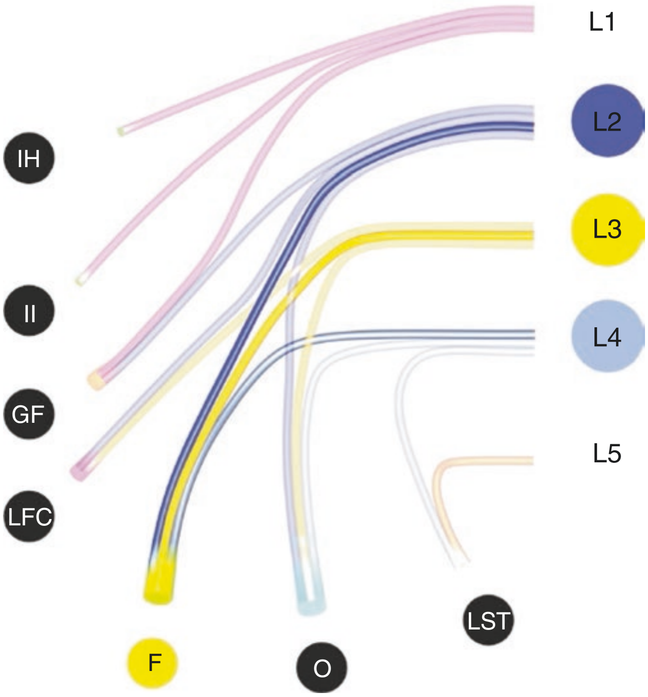
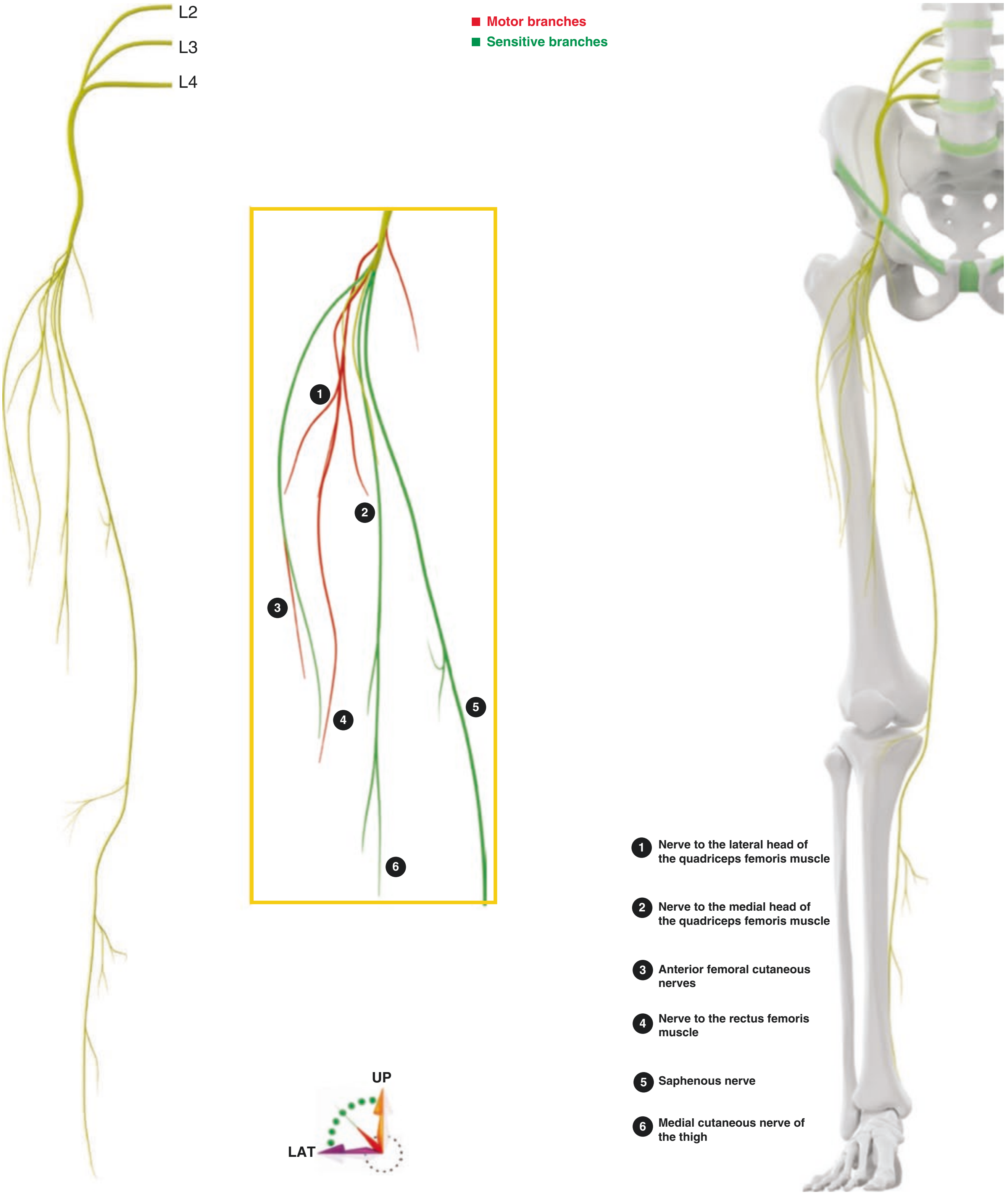


Figure F1. Origin of the femoral nerve.

Electronic Supplementary Material The online version of this chapter (https://doi.org/10.1007/978-3-030-49179-6_14) contains supplementary material, which is available to authorized users.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🟥 Motor branches
🟩 Sensitive branches
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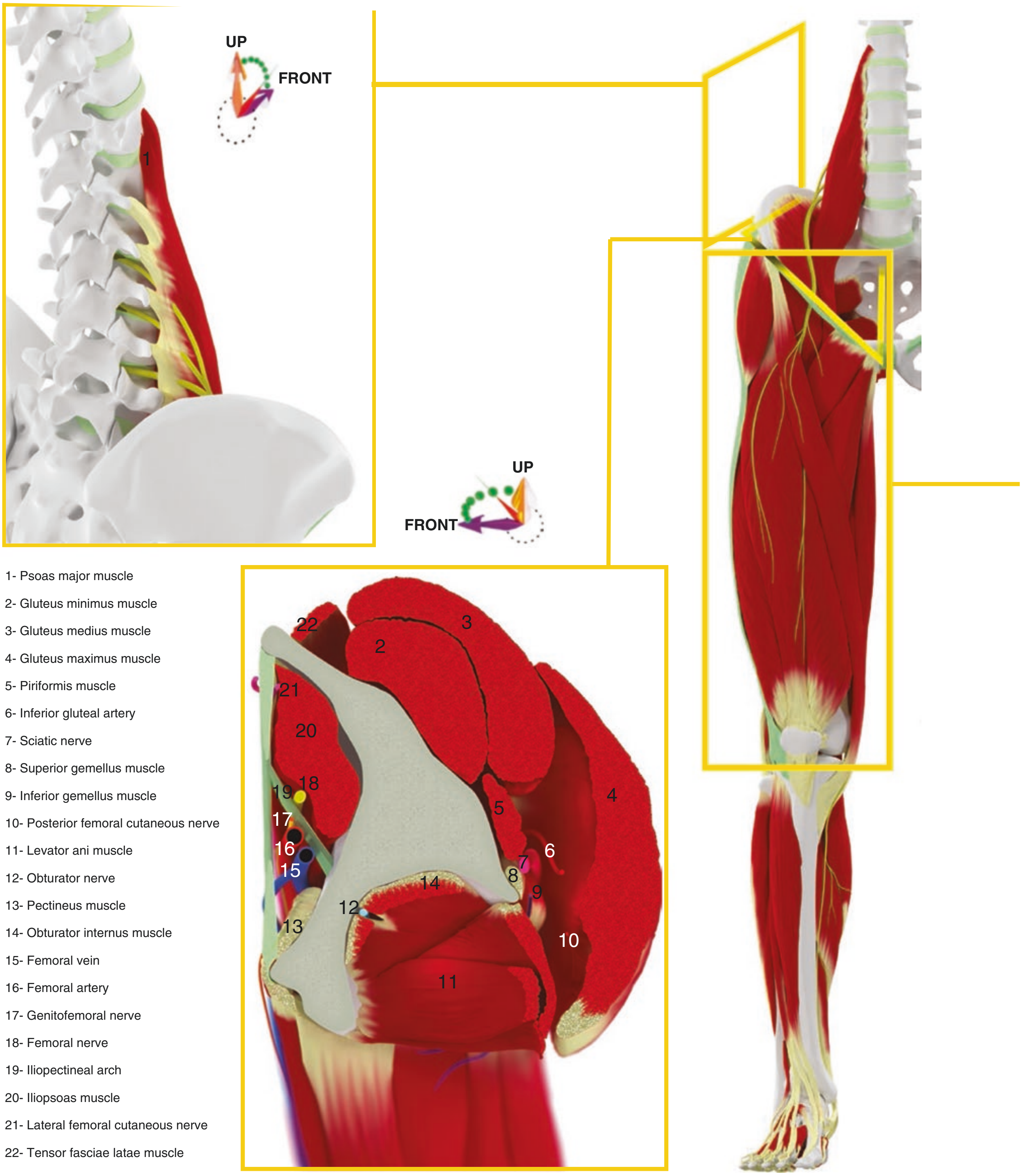
1 Nerve to the lateral head of the quadriceps femoris muscle
2 Nerve to the medial head of the quadriceps femoris muscle
3 Anterior femoral cutaneous nerves
4 Nerve to the rectus femoris muscle
5 Saphenous nerve
6 Medial cutaneous nerve of the thigh

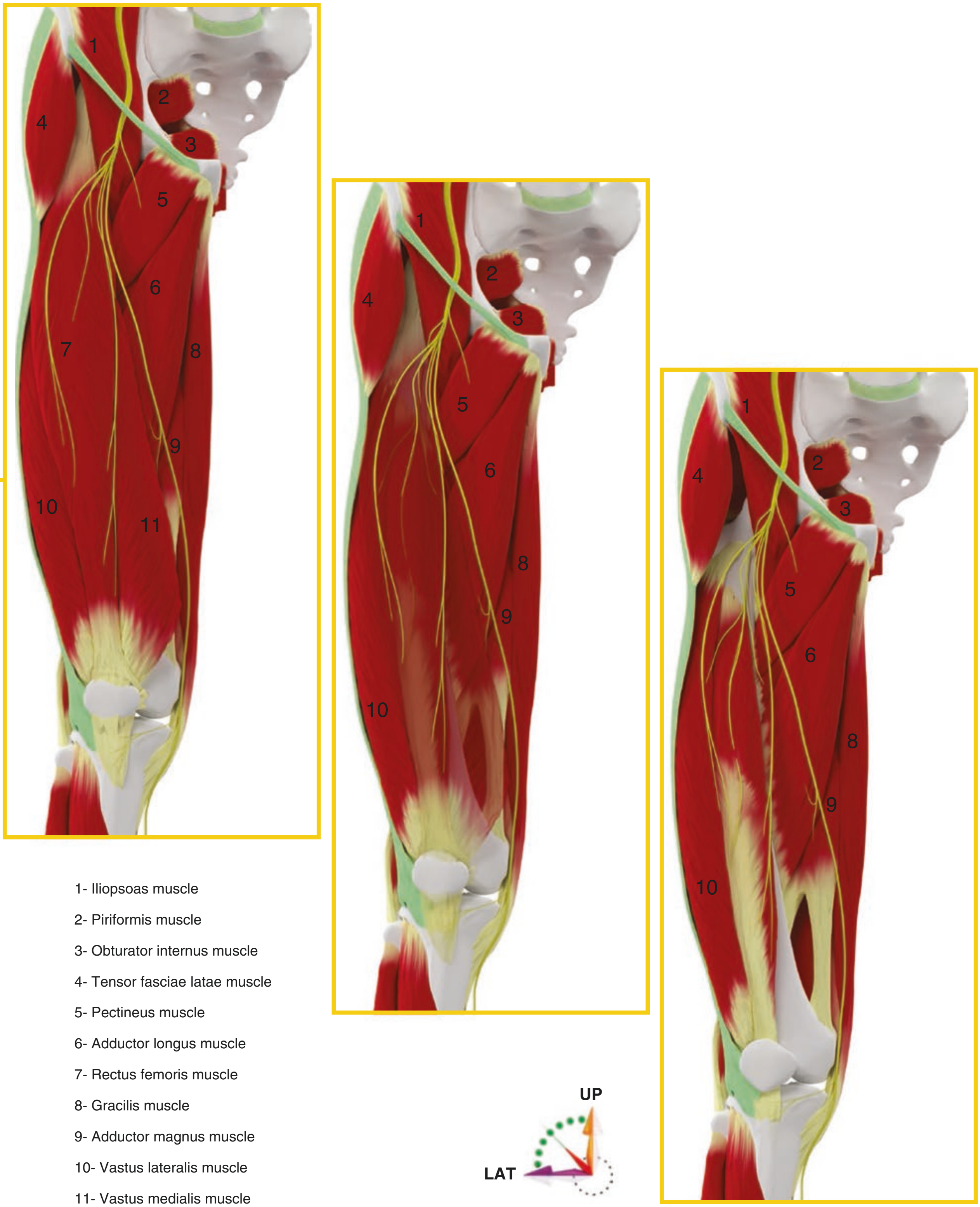
Figure F2. Topographical distribution of the femoral nerve and its relations with bones.

The Femoral Nerve



1- Psoas major muscle
2- Gluteus minimus muscle
3- Gluteus medius muscle
4- Gluteus maximus muscle
5- Piriformis muscle
6- Inferior gluteal artery
7- Sciatic nerve
8- Superior gemellus muscle
9- Inferior gemellus muscle
10- Posterior femoral cutaneous nerve
11- Levator ani muscle
12- Obturator nerve
13- Pectineus muscle
14- Obturator internus muscle
15- Femoral vein
16- Femoral artery
17- Genitofemoral nerve
18- Femoral nerve
19- Iliopectineal arch
20- Iliopsoas muscle
21- Lateral femoral cutaneous nerve
22- Tensor fasciae latae muscle

Figure F3. Muscular relations of the femoral nerve at its origin and at the iliopectineal arch.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1- Iliopsoas muscle
2- Piriformis muscle
3- Obturator internus muscle
4- Tensor fasciae latae muscle
5- Pectineus muscle
6- Adductor longus muscle
7- Rectus femoris muscle
8- Gracilis muscle
9- Adductor magnus muscle
10- Vastus lateralis muscle
11- Vastus medialis muscle
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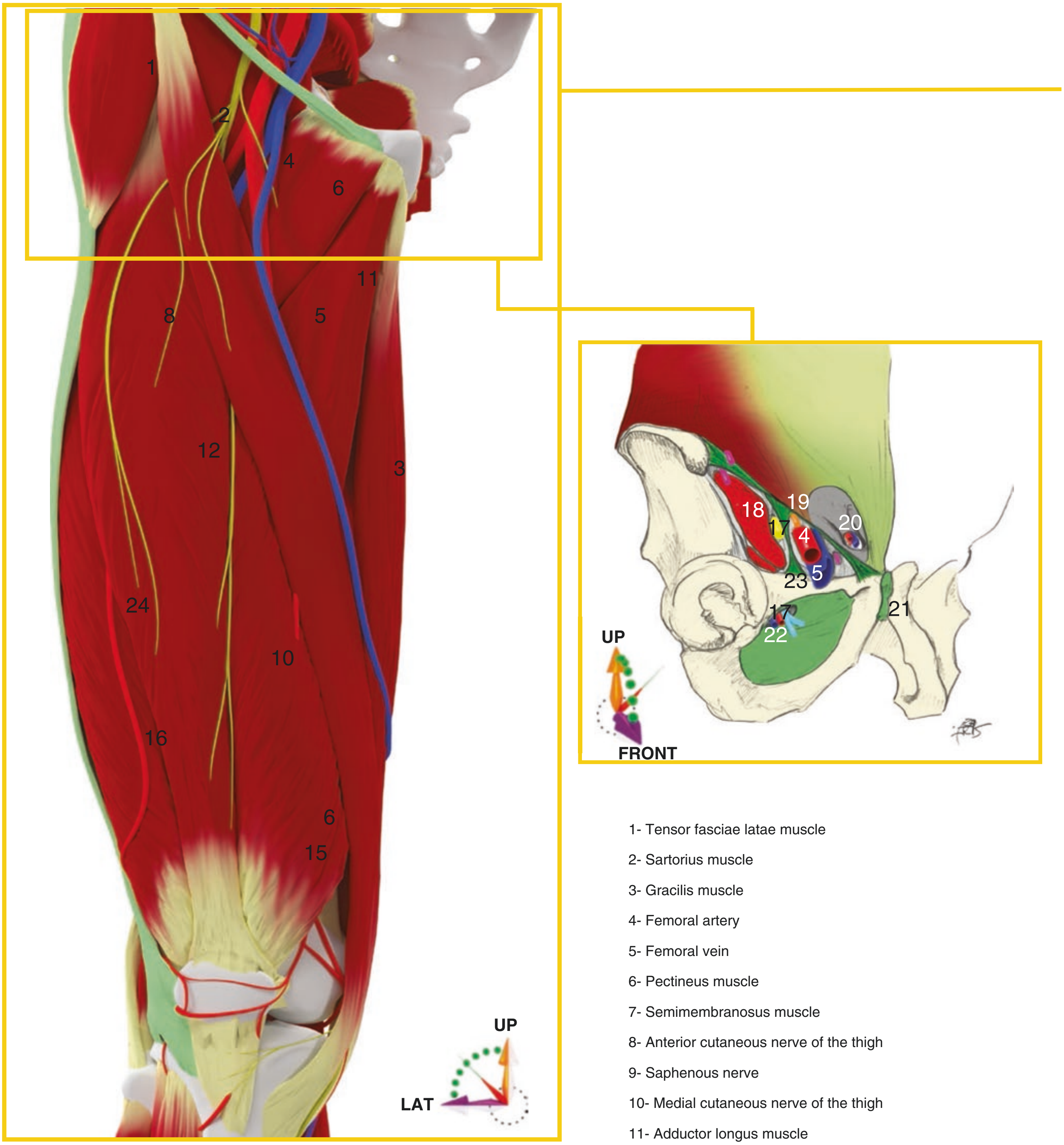
Figure F4. Muscular relations of the femoral nerve in the thigh (anterior view from superficial to deep).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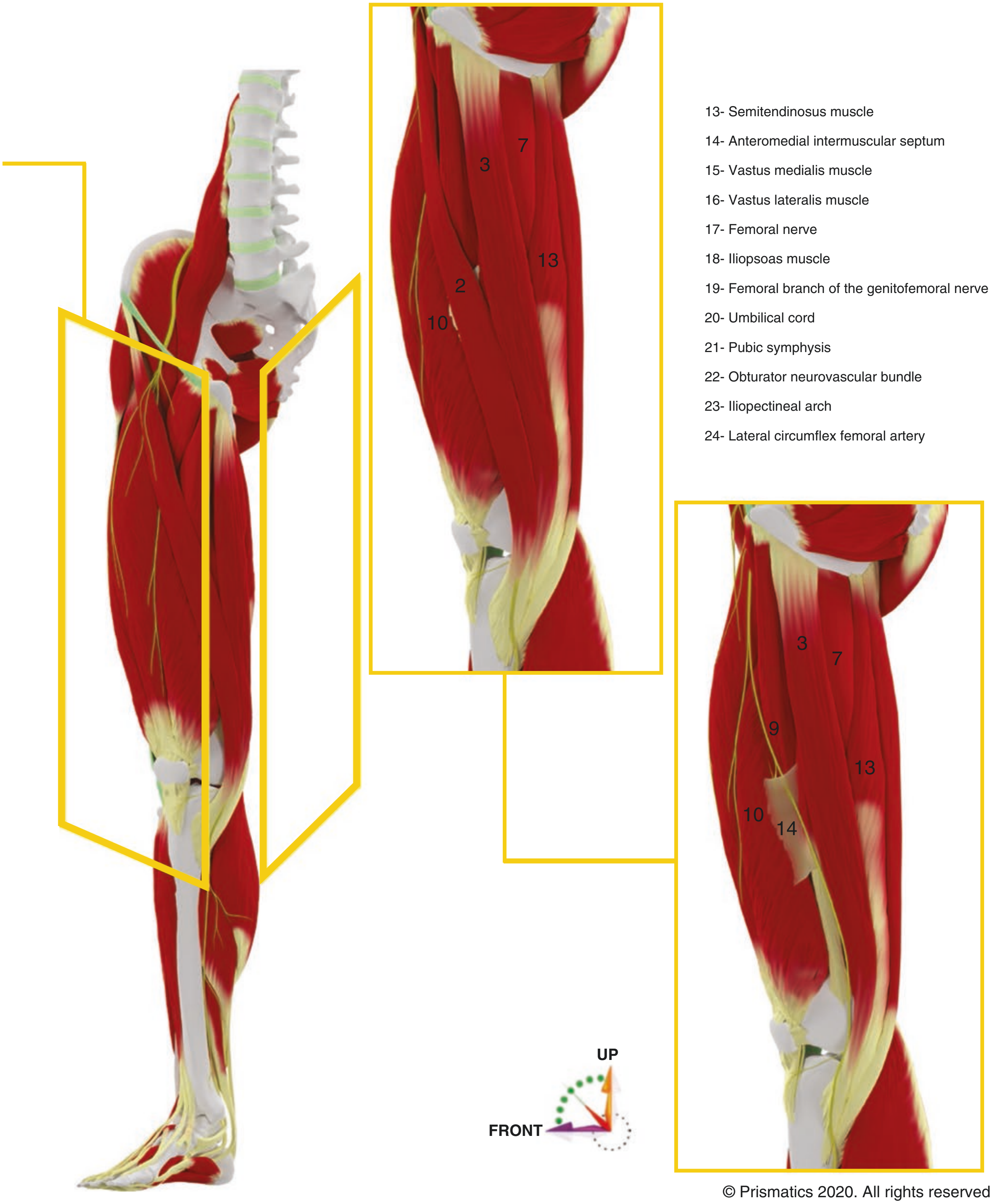
1- Tensor fasciae latae muscle
2- Sartorius muscle
3- Gracilis muscle
4- Femoral artery
5- Femoral vein
6- Pectineus muscle
7- Semimembranosus muscle
8- Anterior cutaneous nerve of the thigh
9- Saphenous nerve
10- Medial cutaneous nerve of the thigh
11- Adductor longus muscle
12- Rectus femoris muscle

Figure F5. Neurovascular and muscular relations of the femoral nerve in thigh (Drawing by P. Rigoard, based on Sobotta's Atlas).



13- Semitendinosus muscle
14- Anteromedial intermuscular septum
15- Vastus medialis muscle
16- Vastus lateralis muscle
17- Femoral nerve
18- Iliopsoas muscle
19- Femoral branch of the genitofemoral nerve
20- Umbilical cord
21- Pubic symphysis
22- Obturator neurovascular bundle
23- Iliopectineal arch
24- Lateral circumflex femoral artery

Figure F6. Muscular relations of the femoral nerve at the adductor canal (internal view).

Terminal Branches

The femoral nerve splits after crossing the femoral canal under the inguinal ligament, in the femoral triangle, formerly named triangle of Scarpa (Figure F4).

This triangle is delimited by the inguinal ligament as a superior base, medially by the gracilis muscle and laterally by the sartorius muscle. The femoral nerve then gives off several terminal branches, including two main branches: the anterior and the posterior branch. Through these branches, the femoral nerve spreads to the muscles of the anterior face of the thigh and to the skin with the anterior cutaneous nerves and the medial cutaneous nerve of the thigh (Figures F2, F4, F8 and F9).

The anterior branch also splits to innervate the muscles of the anterior face of the thigh with the nerves of the sartorius muscle, the nerves of the heads of the quadriceps femoris muscle and the nerves of the pectineus and adductor longus muscles (Figure F4). The nerves of the sartorius muscle spread to the whole muscle from its posterior face at the upper half of its path.

This branch also gives off a vascular branch for the profunda femoral artery and the main, anterior and medial cutaneous nerves of the thigh. These nerves originate from under the sartorius muscle and reach the skin by following its medial face closely or going through it (Figure F5). Finally, they make ramifications at the level of the skin in the anterior part of the thigh.

The posterior branch, also called saphenous nerve, goes down to the knee (Figure F2). It begins at the upper third of the thigh and is initially situated at the medial face of the femoral artery. The saphenous nerve then goes into the adductor canal, which is an extension of the lower part of the femoral triangle (Figure F5).

The adductor canal, formerly known as Hunter's canal, is defined laterally and in front by the medial head of the quadriceps muscle, medially by the vastoadductor intermuscular septum and behind the adductor longus and magnus muscles.

The saphenous nerve then crosses the vastoadductor fascia (also called subsartorial fascia) which links the medial head of the quadriceps femoris muscle to the adductor magnus muscle and the femoral artery from its front and then goes along its medial side (Figure F6). There, it faces the descending genicular artery laterally, which is a collateral branch of the femoral artery. This path is under the sartorius muscle, from the origin of the saphenous nerve to the knee.

At the level of the knee, the saphenous nerve becomes subcutaneous to innervate the medial face of the leg via the infrapatellar branch. It accompanies the great saphenous vein and finally divides into two terminal branches (Figures F6, F10 and F11).

The accessory saphenous nerve is a terminal branch of the femoral nerve that emerges medially and above the other terminal branches. It quickly divides into a superficial branch, which goes along the great saphenous vein until the knee, and a deep branch, which accompanies the femoral artery until the adductor canal. This deep branch finally makes ramifications under the skin of the medial side of the knee.

Motor Function

The femoral nerve takes charge of the flexion of the thigh on the torso and the extension of the leg on the thigh chiefly by innervating the iliopsoas muscle. This same muscle also manages the lateral rotation of the thigh (Figure F7a, b).

The femoral nerve can accessorily provide a function of adduction of the thigh by innervating the pectineus muscle.

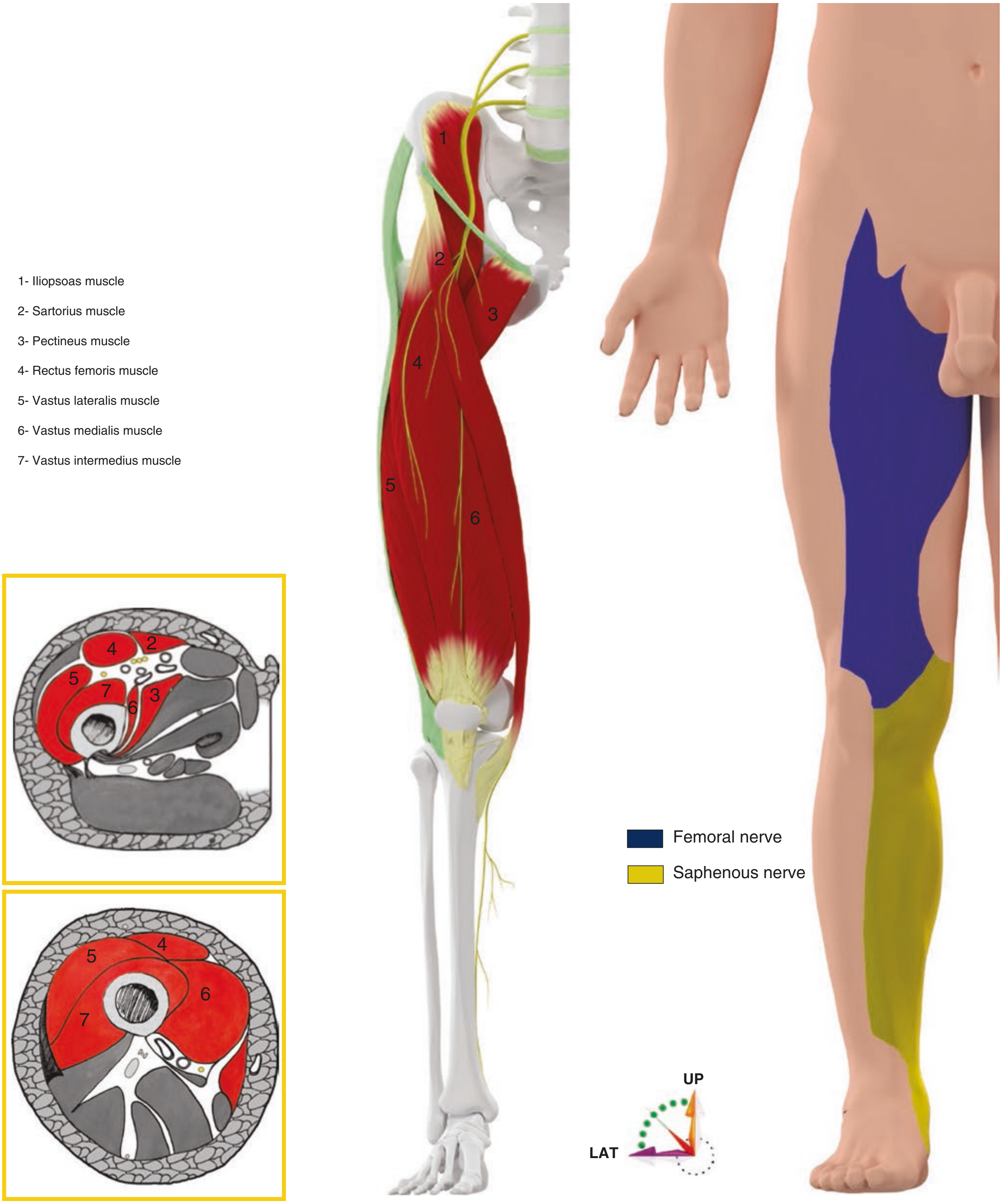
Sensitive Function

The femoral nerve takes charge of the innervation of the anterior face of the thigh, the anterior and medial faces of the knee, the medial half of the leg and the medial side of the ankle (Figure F7).

Anastomoses

The femoral nerve successively makes anastomoses with the following nerves:

- The genitofemoral nerve
- The obturator nerve, under the proximal part of the sartorius muscle, thus forming the subsartorial plexus
- The sciatic nerve in rare circumstances
- The deep fibular nerve, via the saphenous nerve


1- Iliopsoas muscle
2- Sartorius muscle
3- Pectineus muscle
4- Rectus femoris muscle
5- Vastus lateralis muscle
6- Vastus medialis muscle
7- Vastus intermedius muscle
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Femoral nerve
Saphenous nerve
UP
LAT

Figure F7. Motor and sensitive innervation of the femoral nerve.

The Femoral Nerve

1- Lateral femoral cutaneous nerve
2- Anterior cutaneous nerve of the thigh
3- Medial cutaneous nerve of the thigh
4- Nerve to the quadriceps muscle
5- Terminal branch of the femoral nerve
6- Branch of the obturator nerve
7- Sciatic nerve
8- Inferior cluneal nerves
9- Saphenous nerve
10- Posterior femoral cutaneous nerve
11- Great saphenous vein
12- Artery to the quadriceps muscle
13- Deep femoral artery and vein
14- Femoral artery and vein
15- Inferior gluteal artery
16- Deep branch of the deep femoral artery
17- Tensor fasciae latae muscle
18- Rectus femoris muscle
19- Sartorius muscle
20- Adductor longus muscle
21- Vastus lateralis muscle
22- Vastus intermedius muscle
23- Vastus medialis muscle
24- Pectineus muscle
25- Adductor brevis muscle
26- Gracilis muscle
27- Adductor magnus muscle
28- Semimembranosus muscle
29- Long head of the biceps femoris muscle
30- Semitendinosus muscle
31- Gluteus maximus muscle
32- Short head of the biceps femoris muscle
33- Femur
34- Obturator nerve (articular branch to the knee joint)
35- Obturator nerve (cutaneous branch)

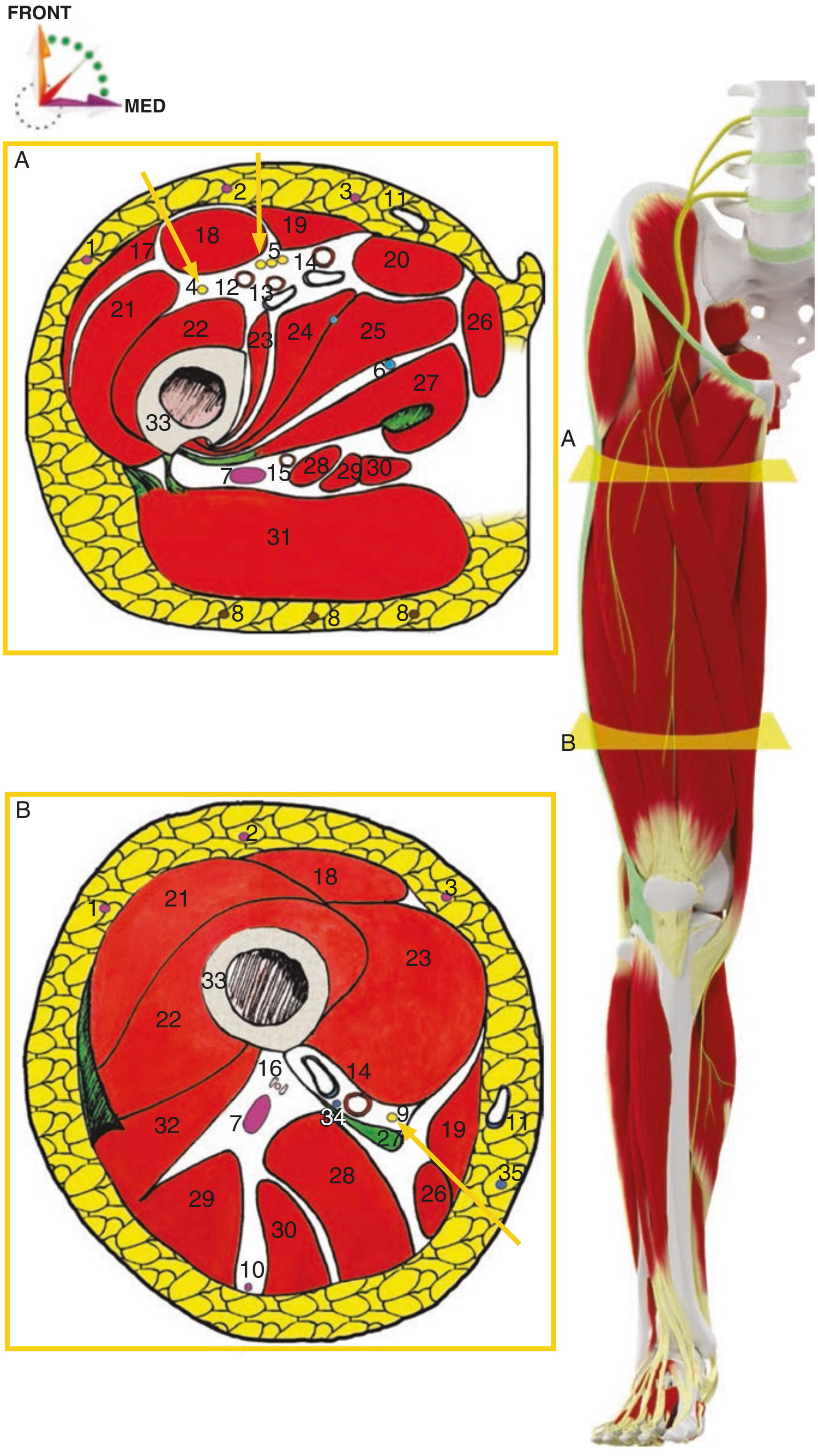


Figure F8. Relations of the femoral nerve in the thigh, axial sections.

1- Lateral sural cutaneous nerve

2- Peroneal communicating nerve

3- Medial sural cutaneous nerve

4- Saphenous nerve

5- Fibular nerve

6- Tibial nerve

7- Sural nerve

8- Deep fibular nerve

9- Superficial fibular nerve

10- Popliteal artery and vein

11- Great saphenous vein

12- Small saphenous vein

13- Anterior tibial artery

14- Fibular artery and vein

15- Posterior tibial artery

16- Patellar ligament of quadriceps femoris muscle

17- Tibia

18- Tibialis anterior muscle

19- Extensor digitorum longus muscle

20- Medial collateral ligament

21- Gracilis muscle

22- Sartorius muscle

23- Synovial bursa

24- Posterior cruciate ligament

25- Semimembranosus muscle

26- Fibula

27- Popliteus muscle

28- Lateral head of the gastrocnemius muscle

29- Plantaris muscle

30- Medial head of the gastrocnemius muscle

31- Extensor hallucis longus muscle

32- Flexor digitorum longus muscle

33- Posterior tibial muscle

34- Peroneus brevis muscle

35- Peroneus longus muscle

36- Soleus muscle

37- Flexor hallucis longus muscle

38- Calcaneal tendon

39- Triceps surae muscle

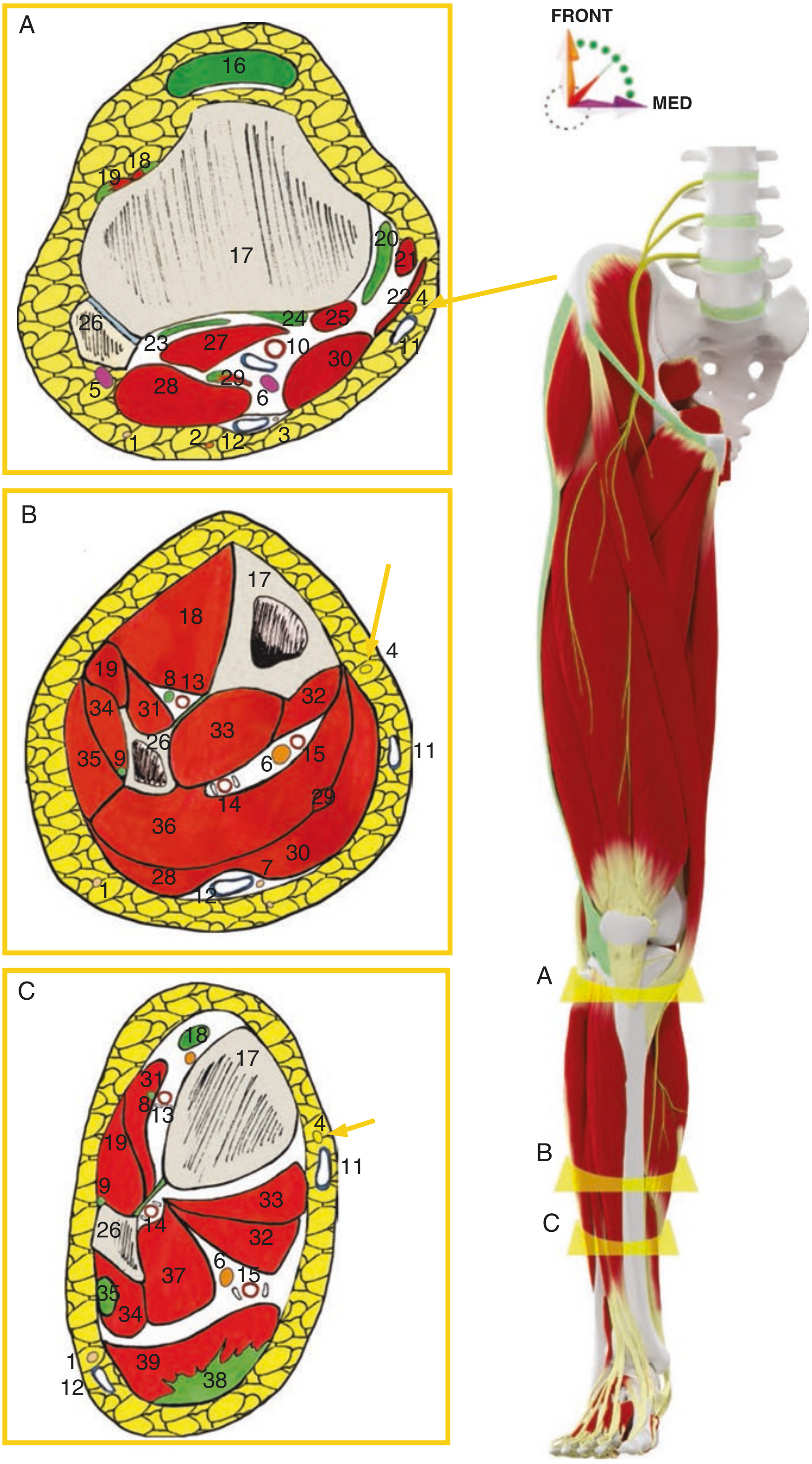
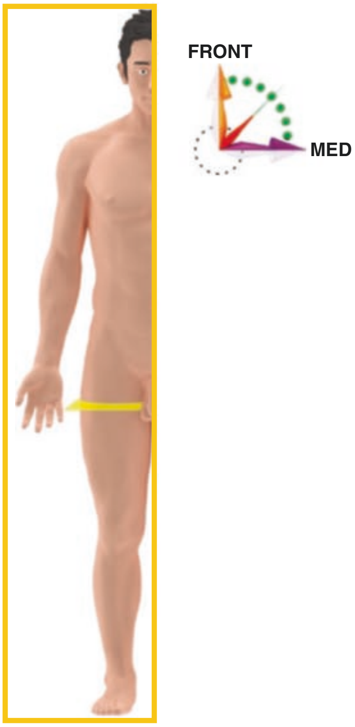


Figure F9. Relations of the femoral nerve in the leg, axial sections.



1- Vastus lateralis muscle

2- Vastus intermedius muscle

3- Tensor fasciae latae muscle

4- Vastus medialis muscle

5- Rectus femoris muscle

6- Sartorius muscle

7- Femur

8- Femoral artery and vein

9- Femoral nerve

10- Deep femoral artery and vein

11- Adductor longus muscle

12- Gracilis muscle

13- Adductor brevis muscle

14- Adductor magnus muscle

15- Semimembranosus muscle

16- Sciatic nerve

17- Anterior branch of the obturator nerve

18- Posterior branch of the obturator nerve

19- Tendon of the biceps femoris muscle

20- Tendon of the semitendinosus muscle

21- Gluteus maximus muscle

22- Pectineus muscle

23- Lateral femoral cutaneous nerve

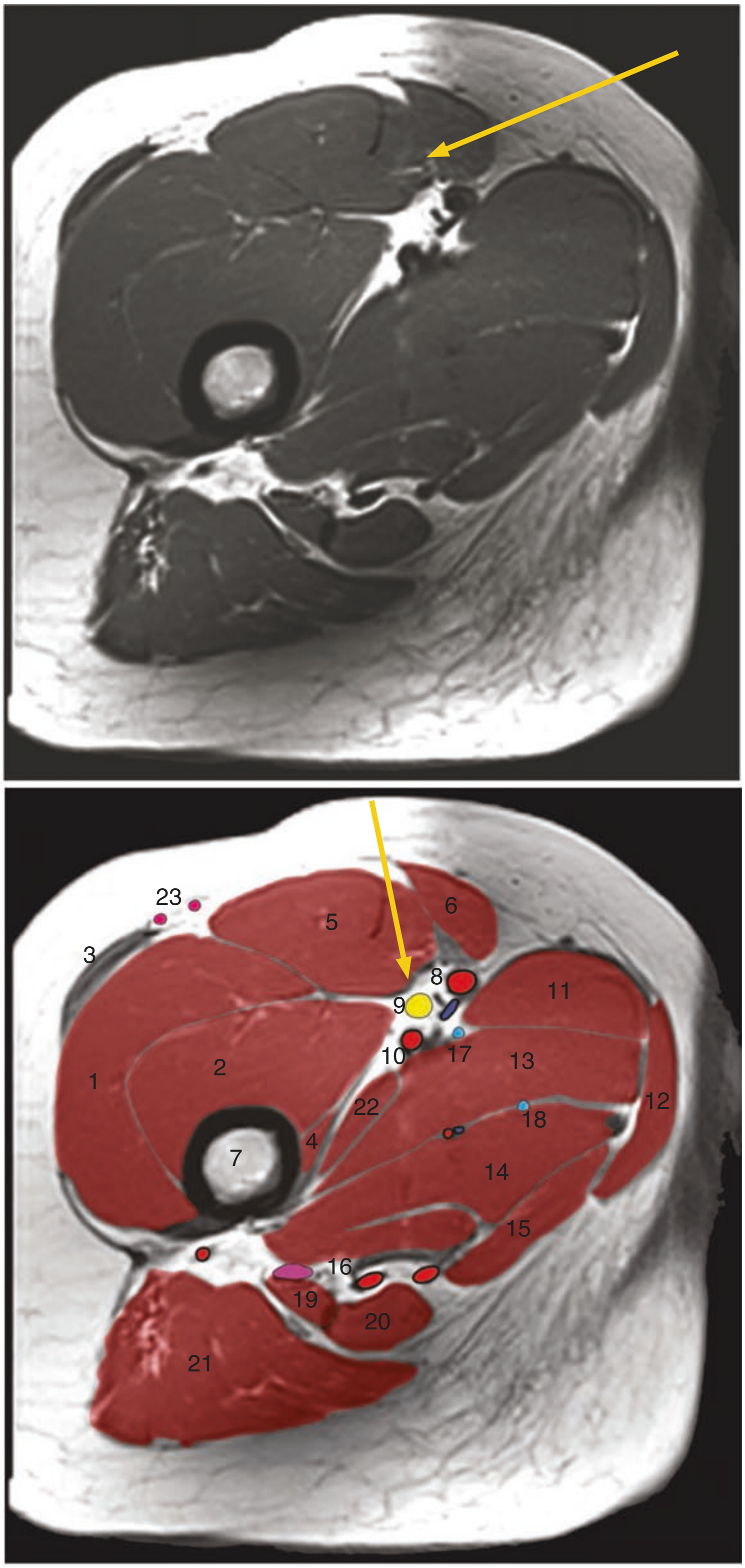
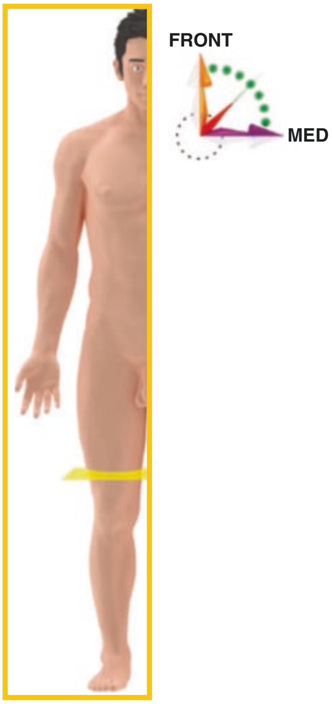


Figure F10. MRI scans at the proximal third of the thigh through the femoral nerve.



1- Vastus lateralis muscle

2- Vastus intermedius muscle

3- Rectus femoris muscle

4- Vastus medialis muscle

5- Femur

6- Short head of the biceps femoris muscle

7- Saphenous nerve

8- Femoral artery and vein

9- Perforating artery and vein of the deep femoral artery and vein

10- Common fibular nerve

11- Tibial nerve

12- Posterior femoral cutaneous nerve

13- Long head of the biceps femoris muscle

14- Adductor magnus muscle

15- Sartorius muscle

16- Gracilis muscle

17- Semimembranosus muscle

18- Semitendinosus muscle

19- Great saphenous vein

20- Obturator nerve (articular branch to the knee joint)

21- Obturator nerve (cutaneous branch)

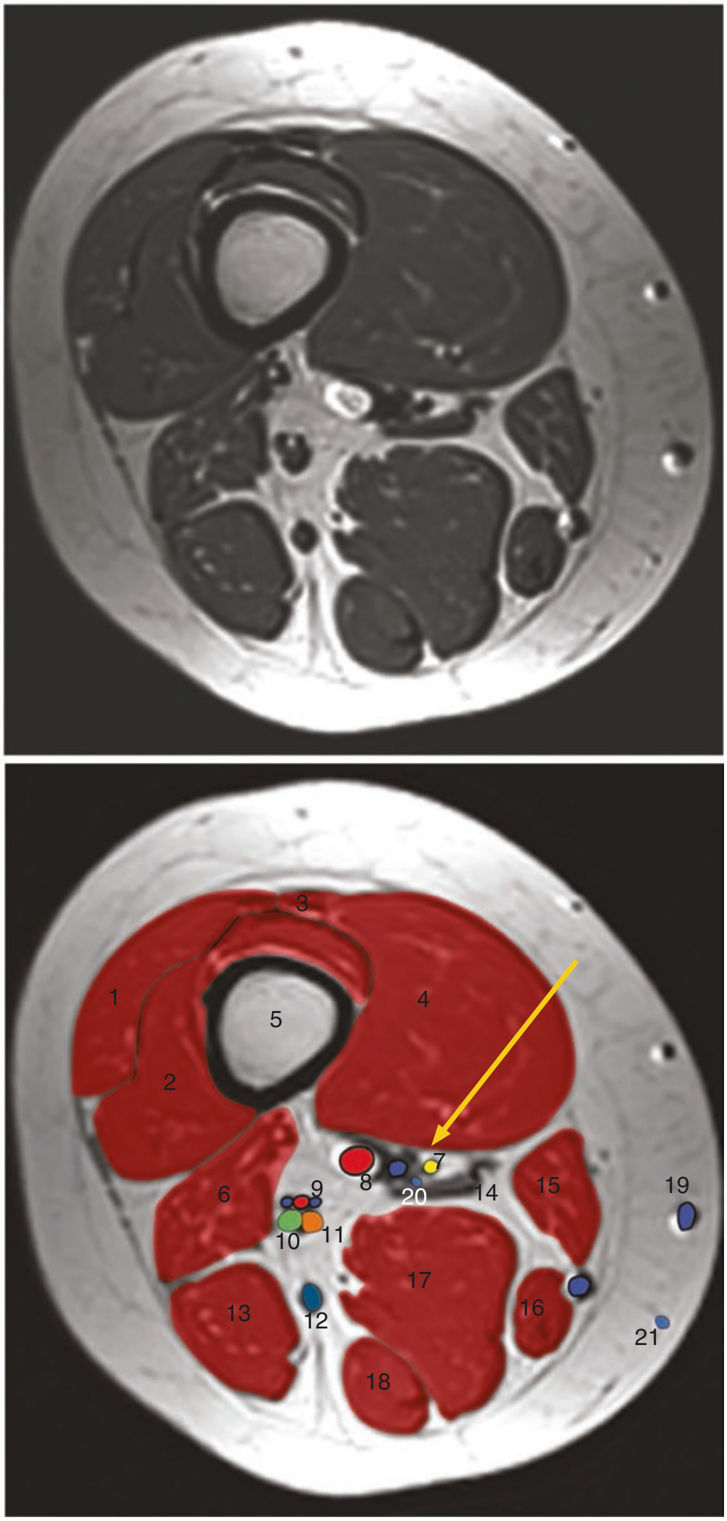


Figure F11. MRI scans at the distal third of the thigh through the femoral nerve.

Pathology

Femoral Nerve Syndrome or Femoral Neuralgia

The femoral nerve is a terminal branch of the lumbar plexus.

It leaves the pelvis under the femoral arch, at which point it faces the femoral artery medially. This arch is closed at the top by the iliopectineal ligament and can be subject to an entrapment neuropathy (Figures F12 and F13).

Aetiology

- Compression: This entrapment neuropathy can be caused by repeated hip movements that generate a compression of the nerve at this level, a laborious pregnancy, an injury caused by a tumour, an expansion of the psoas muscle or a surgery, for example (Figure F13).

Clinical Significance

- Sensitive signs: These concern the anterior face of the thigh and can elicit hip pain. This pain can appear more clearly during hip movements that compress the nerve.
- Motor signs: The femoral nerve innervates the iliopsoas muscle and the greater part of the muscles of the anterior compartment of the thigh. Chronic damage can cause a paresis and an amyotrophy of the quadriceps femoris muscle. The patient's ability to extend their leg on the thigh is reduced or can even become impossible. Since the iliopsoas muscle is innervated prior to the femoral nerve damage, the flexion of the thigh on the torso is generally sustained.

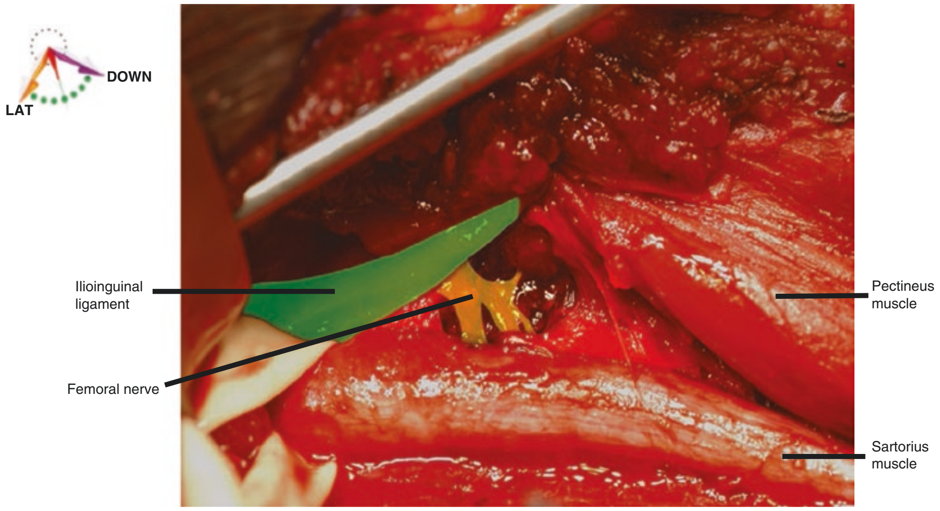
Explorations

- An electroneuromyography shows signs of a denervation in the muscles innervated by the femoral nerve.
- Imaging of the lumbar vertebrae eliminates the possibility of an injury from a compression or a discoradicular conflict on L3 or L4.

Treatment

In cases of proven entrapment neuropathy, surgical treatment consists of a section of the femoral ligament. Chances of morbidity are close to zero regardless of the surgical access.

This surgery generally obtains excellent results regarding both the pain and the functional recovery of the quadriceps muscle.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Ilioinguinal ligament
Femoral nerve
Pectineus muscle
Sartorius muscle

Figure F12. Operative view of a decompression of the femoral nerve at the femoral triangle.

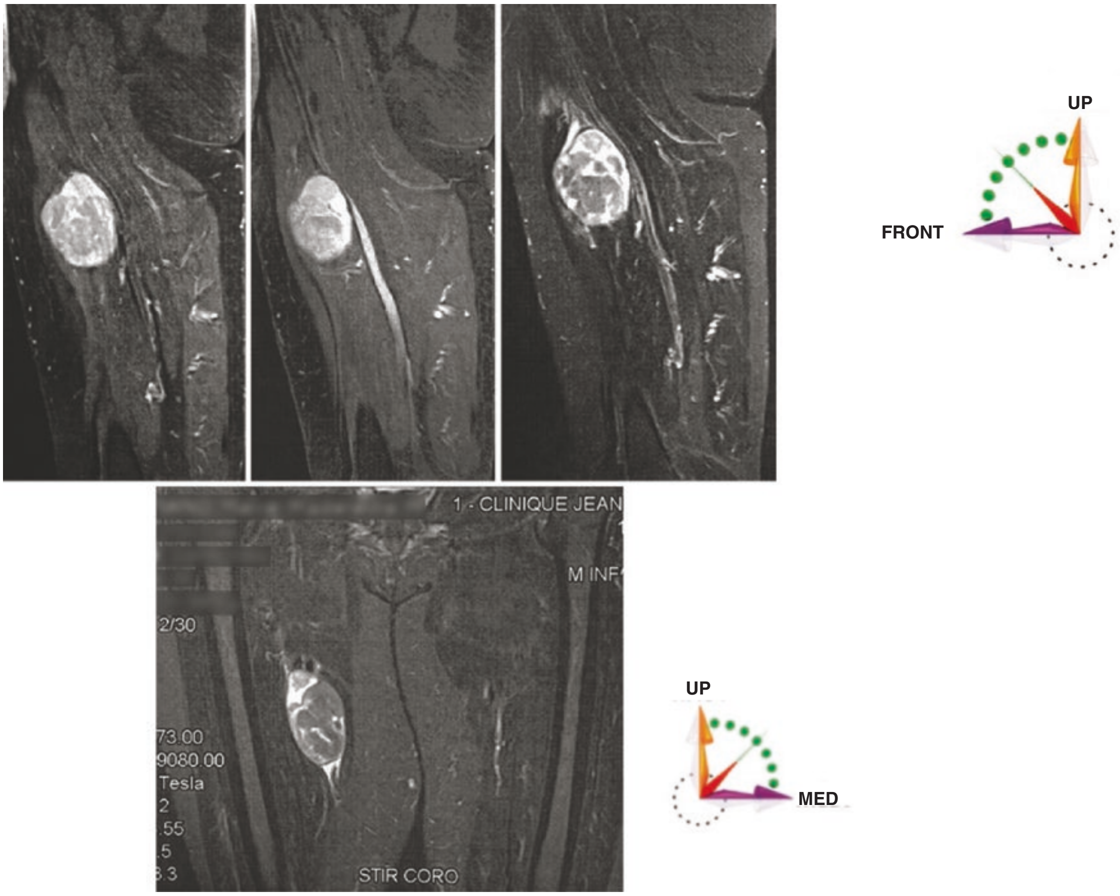
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Figure F13. MRI scan of the thigh (coronal sections) performed after the apparition of a femoral neuralgia in a context of weight loss and evolving swelling of the thigh. Discovery of a soft tissue tumour in contact with the femoral branches.

Morphological Data: Sono Anatomy

Installation

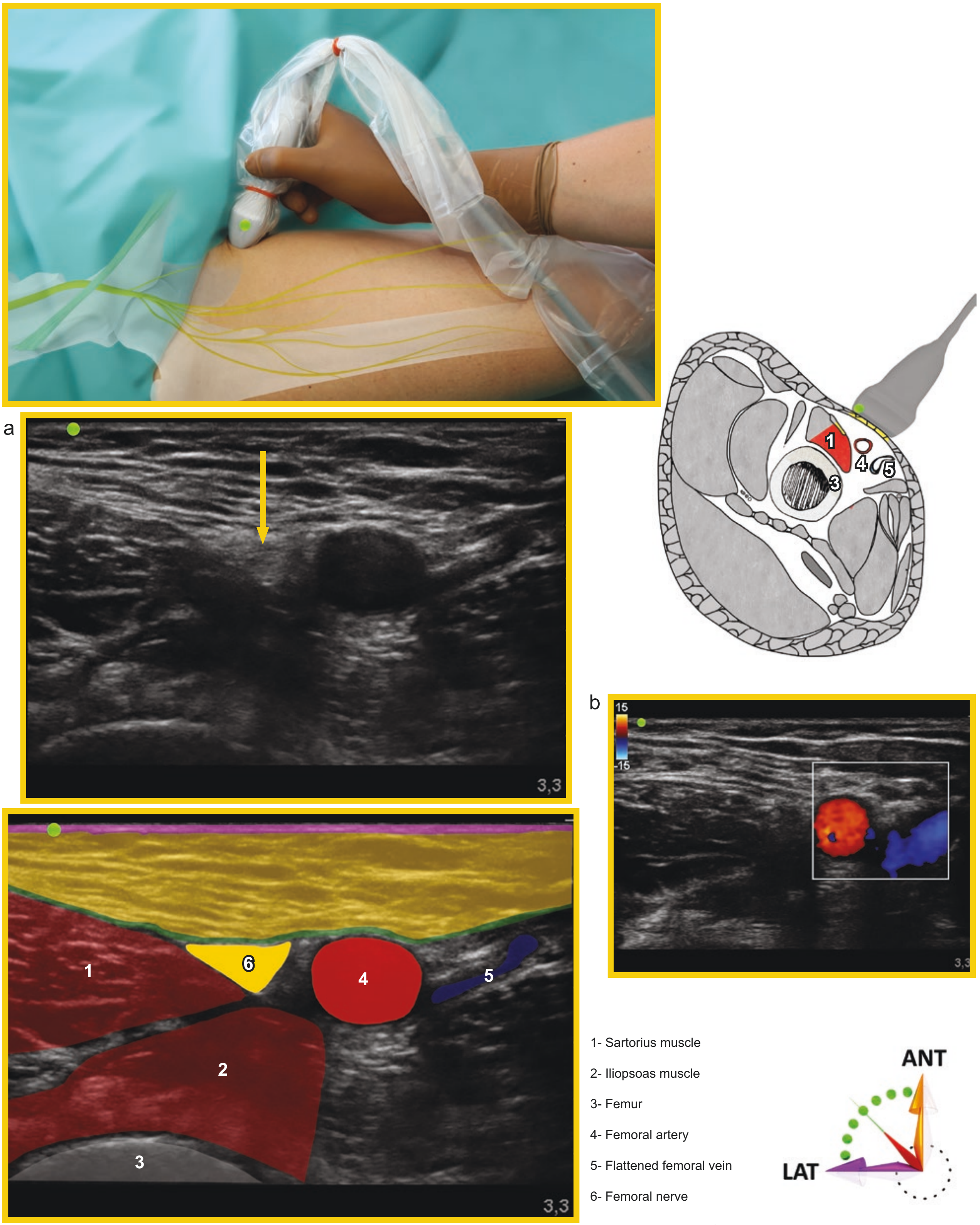
The patient is placed in supine position, with slight external rotation of the lower limb. In overweight patients, it may be interesting to tension the abdominal adipose panicle with “Elastoplast™” strips to better release the inguinal flexion fold.

Equipment and Location

– Probe type: Linear, high frequency.
– Probe axis: The probe is placed in the flexion fold of the thigh in a transverse (axial), slightly oblique caudally (bottom and inside) and medially, so as to be fully positioned in the flexion fold.

Ultrasound Procedure

Once the probe is positioned in the flexion fold, vascular structures are quickly visualized using colour Doppler, particularly the femoral artery, which serves as a medial landmark. The femoral nerve is located at the deep face of the fascia iliaca and at the ventral surface of the iliopsoas muscle on which it rests. The femoral nerve is presented at this level as a more or less flattened oval structure in the frontal plane, generally already spread out; its different branches are sometimes difficult to distinguish, giving it a generally honeycombed appearance. Optimized anisotropy provides the best view according to the contrasts between the different structures. Among the branches of division of the femoral nerve are the sensitive branches to the anterior surface of the thigh, which perforate the fascia iliaca at a variable level. At the level of the inguinal fold, these branches for cutaneous use are sometimes already found on the surface of the fascia iliaca. Their identification by a “lift” movement of the probe makes it possible to go up to the level where these sensitive branches perforate the fascia iliaca, so as to approach and possibly stimulate them. The use of colour Doppler echoes makes it possible to differentiate them from vascular structures: the femoral artery and particularly the circumflex iliac artery, which can pass through the image, from the medial edge to the lateral edge of the screen, in front of the femoral nerve (Figures F14–F16).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1- Sartorius muscle
2- Iliopsoas muscle
3- Femur
4- Femoral artery
5- Flattened femoral vein
6- Femoral nerve

Figure F14. (**a**) Ultrasound transversal views of the femoral nerve before its division at the proximal part of the thigh. (**b**) Doppler mode view.

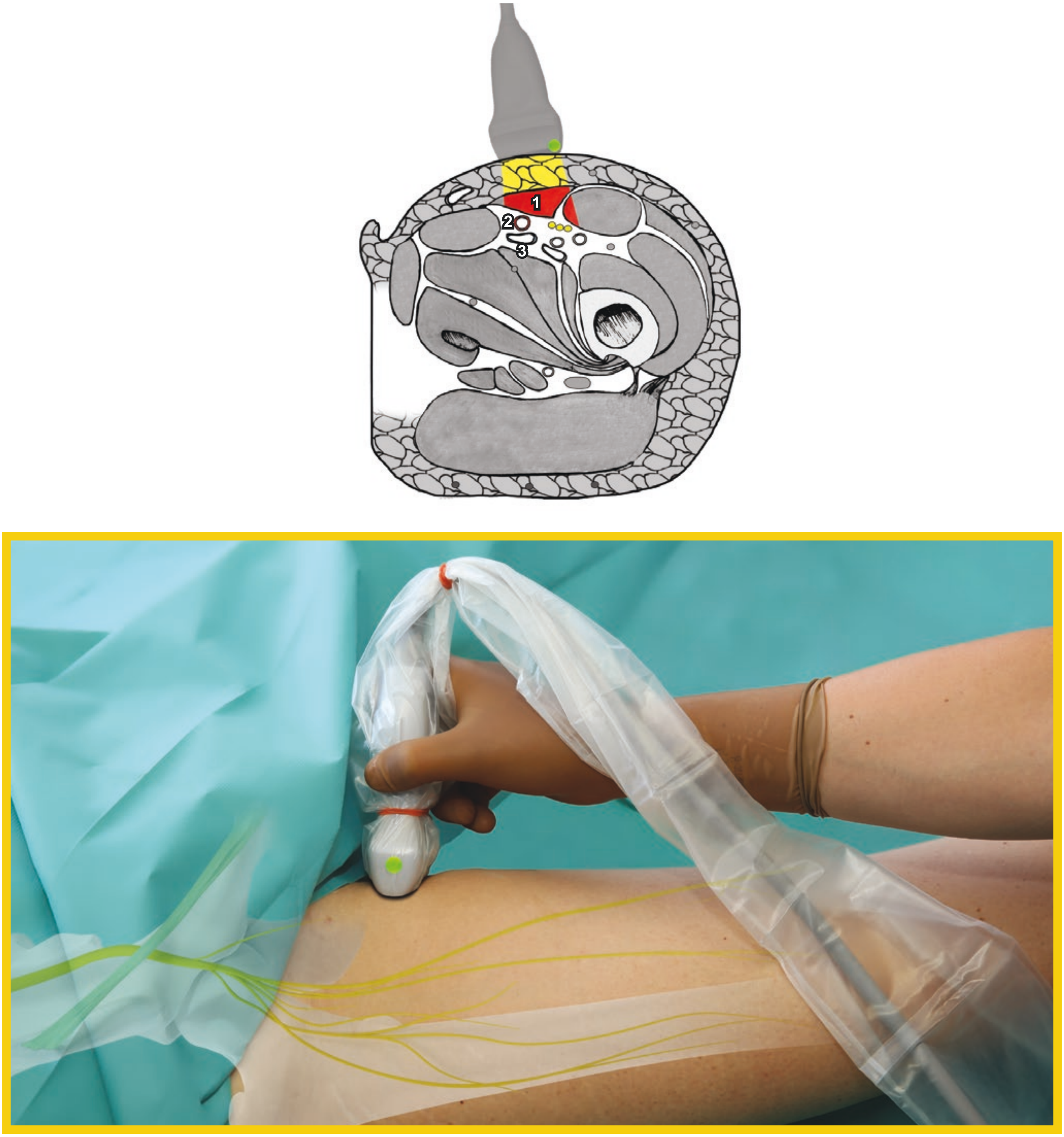

Figure F15. Ultrasound probe optimal positioning to visualize the femoral nerve at the proximal part of the thigh.

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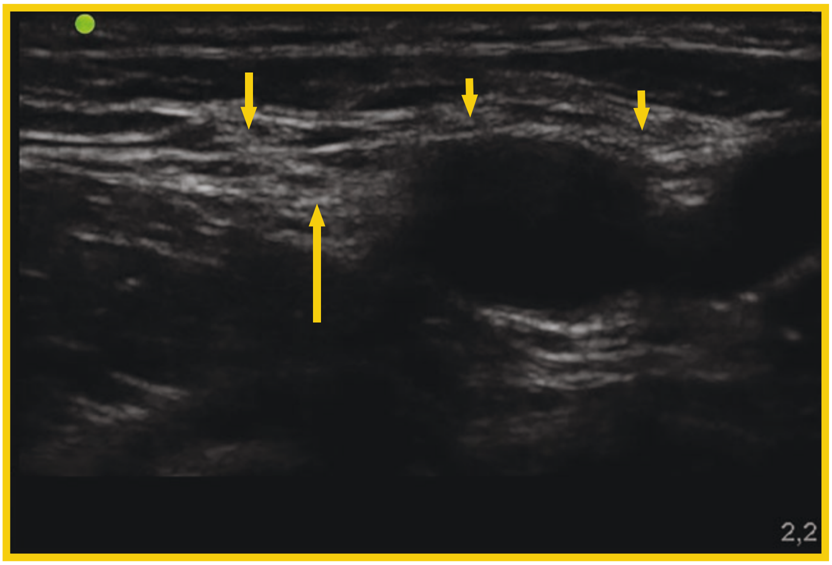


1- Sartorius muscle

2- Femoral artery

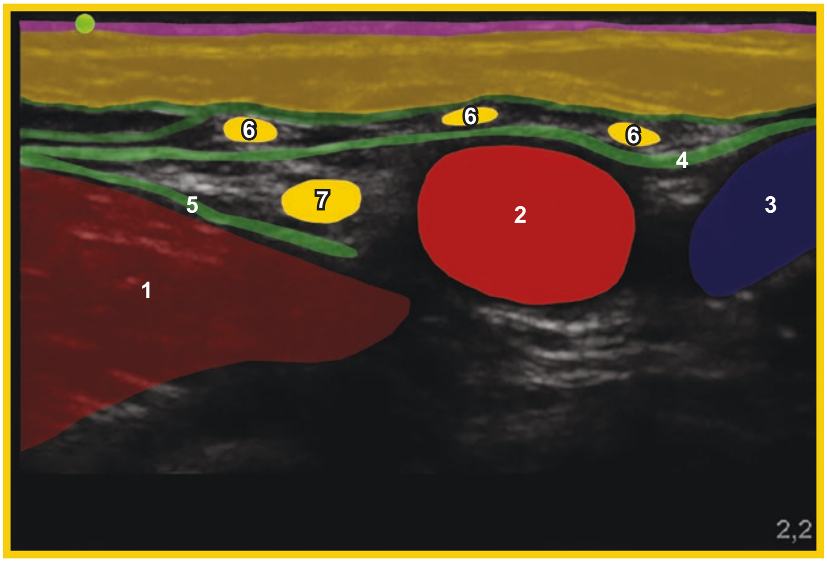
3- Femoral vein

4- Fascia lata

5- Iliac fascia

6- Division branches of the femoral nerve

7- Femoral nerve



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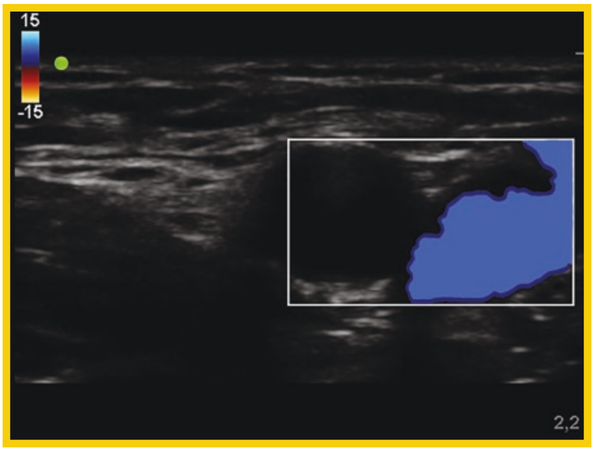


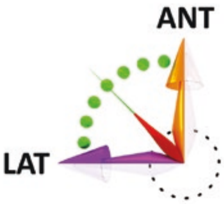


Figure F16. (**a**) Ultrasound transversal views of the femoral nerve at the level of its division at the proximal part of the thigh and its branches after crossing the fascia lata. (**b**) Doppler mode view.

Interventional Procedure

Infiltration/Test Block

Indications

Affected by the anterior branch of the femoral nerve, responsible for neuropathic pain in the anterior-inferior part of the thigh, above the knee.

Technique

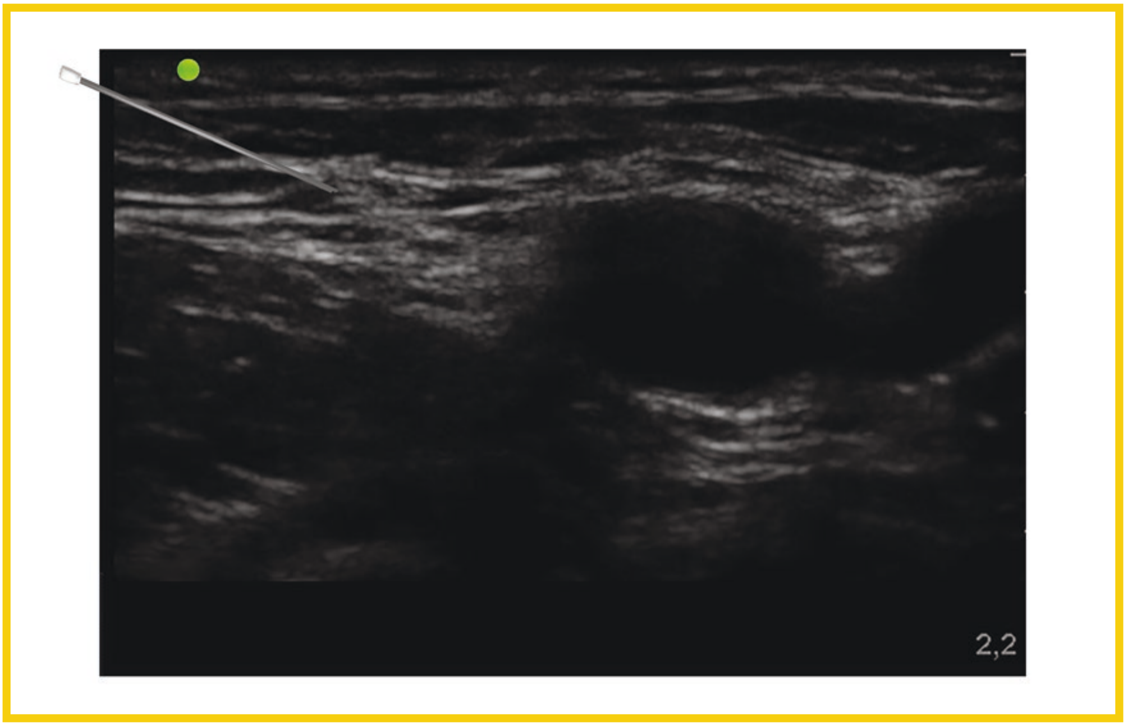
After ultrasound identification of the above-mentioned nerve and its division with the anterior branch, the needle is positioned “in plane”. It is inserted between the two fascias, with a lateral to medial progression to avoid vascular punctures (the femoral artery being medial to the nerve). For the diagnostic test block, use of low volume local anaesthetic <1 mL is preferred. To make a therapeutic test block, the volume used may be larger but with a risk of making a non-selective femoral block by diffusion (Figure F17).

PNS

Peripheral nerve stimulation of this nerve is not performed in clinical practice for the same reasons as those given for the branches of the obturator nerve.

RFP

We have not found any published experiment with pulsed radiofrequency of the femoral nerve.



1- Sartorius muscle

2- Femoral artery

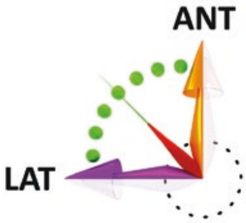
3- Femoral vein

4- Fascia lata

5- Iliac fascia

6- Division branches of the femoral nerve

7- Femoral nerve



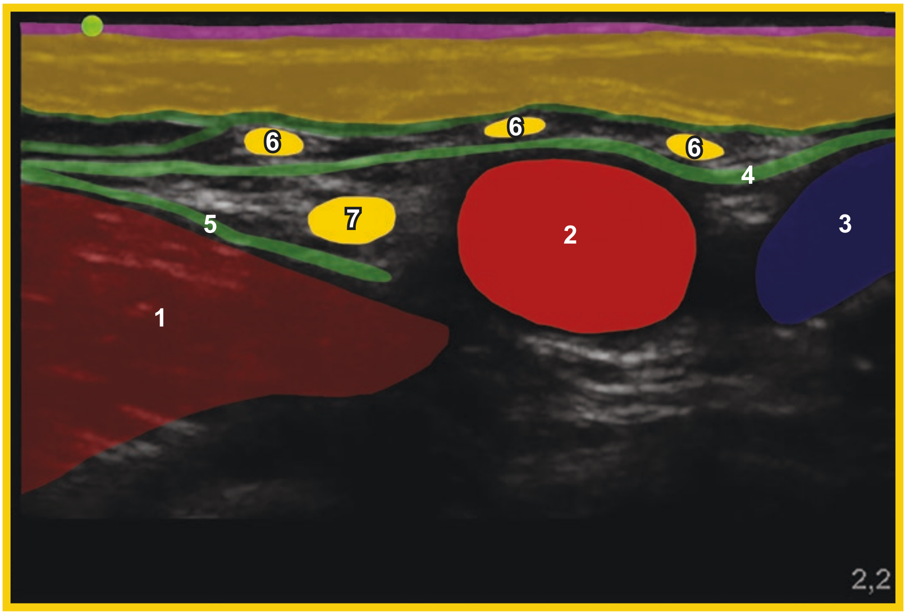


Figure F17. Femoral nerve anaesthetic block (in-plane technique).

Morphological Data: Sonoanatomy

Installation

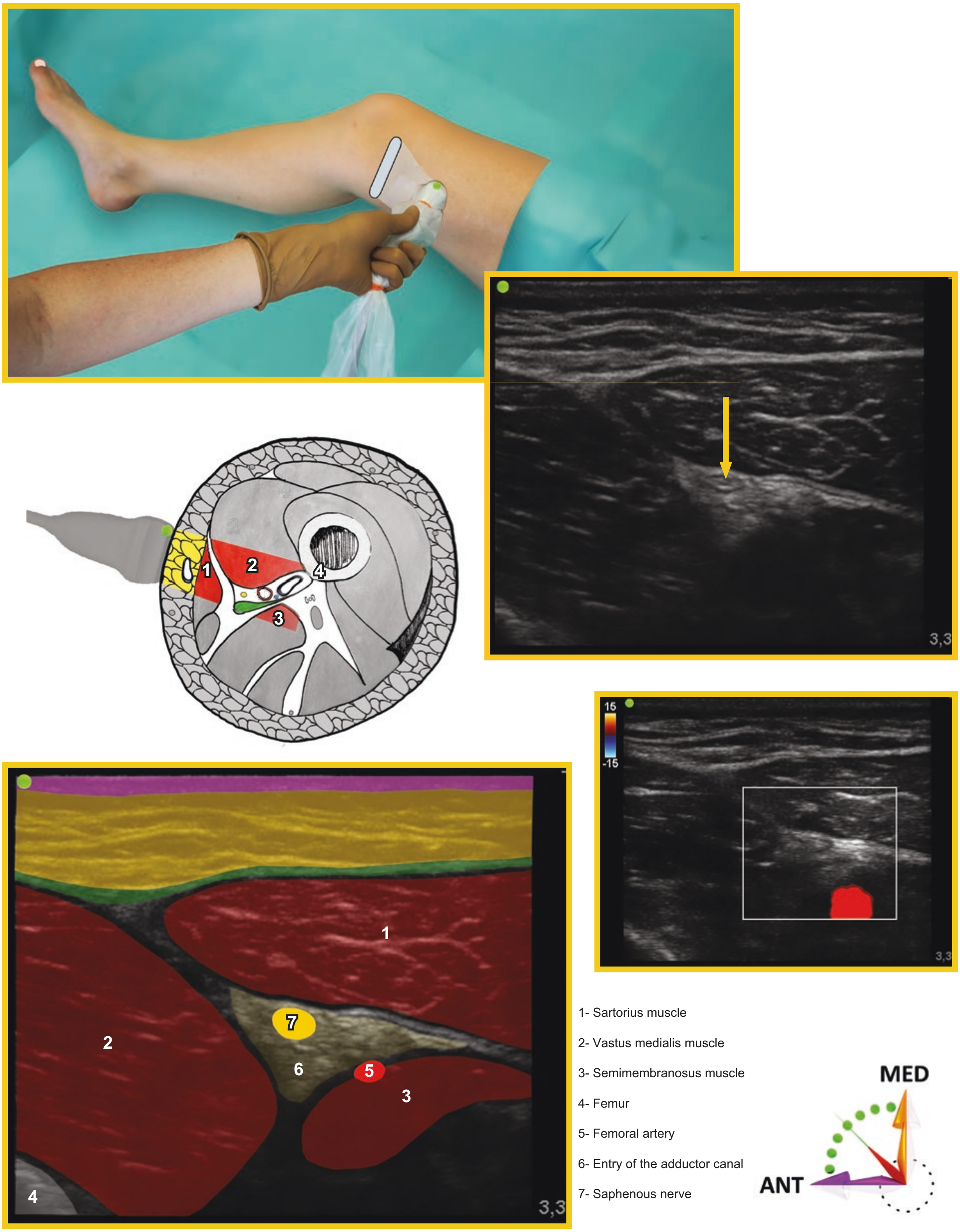
The patient is in supine position with external rotation and slight abduction of the thigh.

Equipment and Location

- Probe type: linear, high frequency
- Probe axis: axial

Ultrasound Procedure

The probe is initially placed at the medial surface of the thigh, approximately at the junction of the medial and distal third of the thigh. This generally corresponds to a horizontal line passing 12 cm above the cranial edge of the patella. Once the probe is initially positioned, care should be taken to identify the superficial femoral artery by a rostro-caudal lift movement, with the help of the colour Doppler, and then the descending geniculate artery, located on the deep face of the sartorius muscle. It is accompanied on its posterior surface by the femoral vein. In contact with these vascular structures, generally placed on the anterior surface of the femoral artery, the saphenous nerve can be followed in the continuity of the artery. At the adductor canal, the saphenous nerve is a satellite of the descending geniculated artery. It comes from the femoral artery just before it dives into the deep face of the adductor magnus tendon. More distally, while the femoral artery goes in a popliteal direction, the saphenous nerve becomes a satellite of the descending genicular artery. It can be identified among three anatomical elements: the sartorius muscle on the surface, the more ventral vast medial muscle and, more deeply, the superficial femoral artery. It should be noted that the ventral position of the saphenous nerve in relation to the superficial femoral artery is not systematic, as it may exceptionally be located on its dorsal surface. The saphenous nerve then forks into sartorial and infrapatellar branches, on average 2.7 cm from the lower edge of the patella and 6.6 cm in the medial (Figures F18–F20).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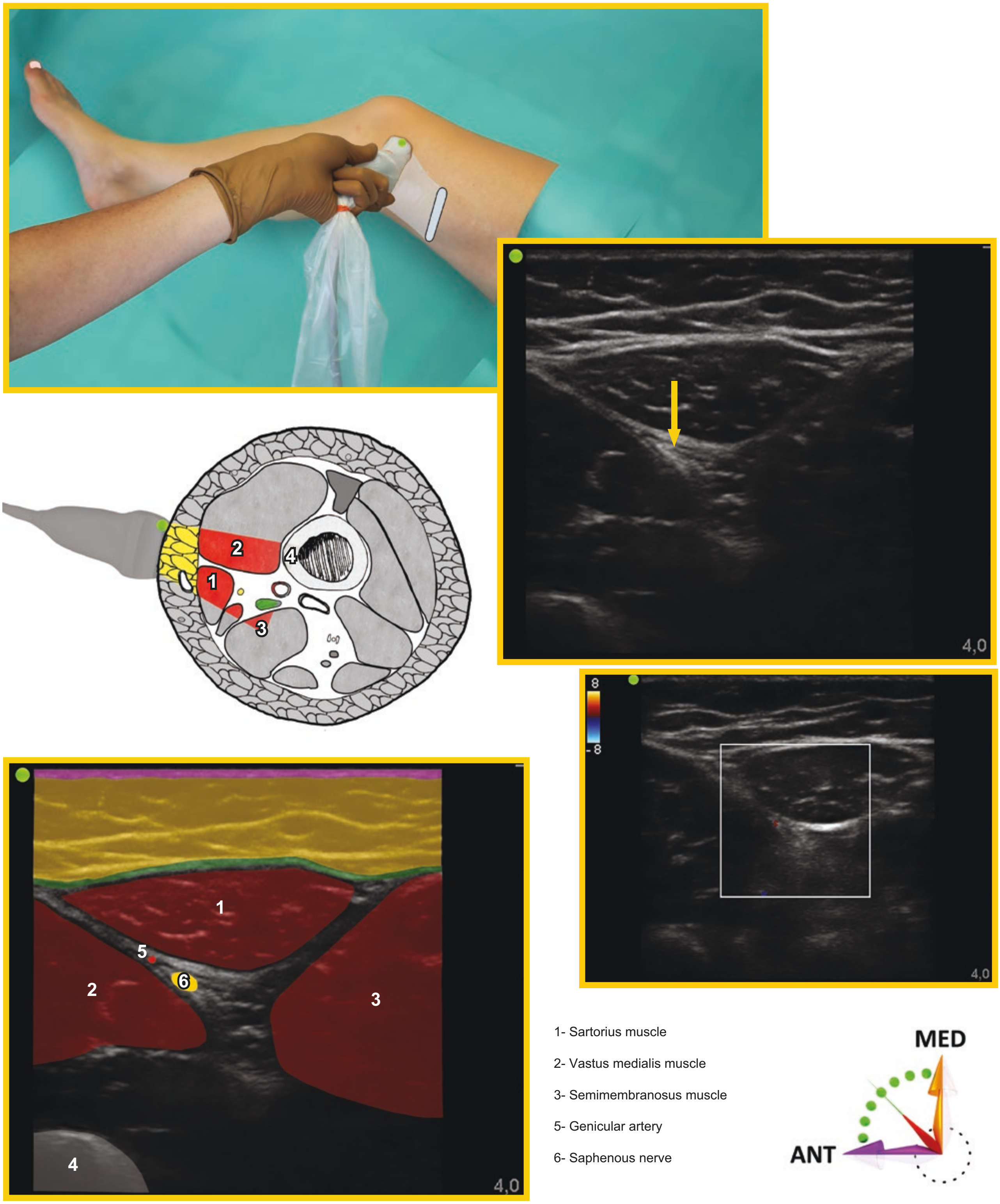
1- Sartorius muscle
2- Vastus medialis muscle
3- Semimembranosus muscle
4- Femur
5- Femoral artery
6- Entry of the adductor canal
7- Saphenous nerve
MED
ANT

Figure F18. (**a**) Ultrasound transversal views of the saphenous nerve at the thigh distal third. (**b**) Doppler mode view.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4,0
1- Sartorius muscle
2- Vastus medialis muscle
3- Semimembranosus muscle
5- Genicular artery
6- Saphenous nerve
MED
ANT

Figure F19. (**a**) Ultrasound transversal views of the saphenous nerve at the adductor canal level. (**b**) Doppler mode view showing the genicular artery.

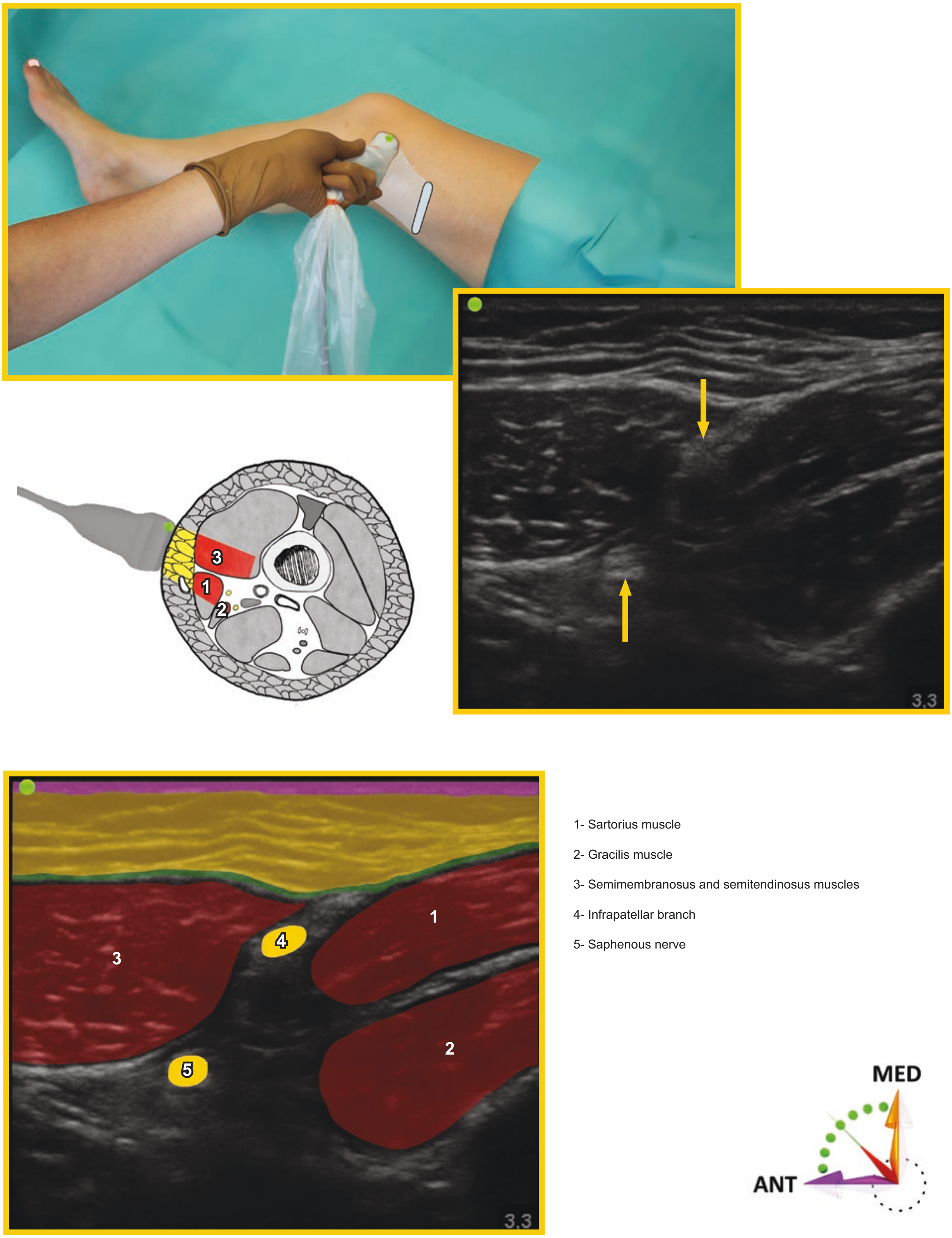
3
1
2
3,3
1
3
4
2
5
3,3
1- Sartorius muscle
2- Gracilis muscle
3- Semimembranosus and semitendinosus muscles
4- Infrapatellar branch
5- Saphenous nerve
MED
ANT

Figure F20. Ultrasound transversal views of the infrapatellar branch of the saphenous nerve.

Interventional Procedure

Infiltration/Test Block

Indication

Neuropathies secondary to arthroscopies in total knee replacements or recurrent patella dislocations. The test block must be performed at a distance from the lesion.

Technique

After ultrasound identification of the above-mentioned nerve, the infiltration needle is placed "in plane". The probe is positioned transversely.

The puncture is carried out at the front edge of the probe in the posterior direction, and the test block requires small volumes of local anaesthetic.

PNS

Indications

- Neurinoma or proximal neuropathy of the saphenous nerve
- Distal neuropathy of saphenous branches

Technique

After ultrasound identification of the above-mentioned nerve, the stimulation needle is positioned "out of plane". The lead is positioned in the craniocaudal direction. Hydrolocalization is performed, and the stimulation lead is placed in contact with the nerve using the guide needle. For optimal positioning of the lead, it is recommended to visualize at least two of the lead in contact with the nerve. For infrapatellar neuropathies, ultrasound provides limited assistance. The electrode is then positioned along a transverse axis at the anteromedial surface of the knee. The insertion point of the stimulation lead is at maximally medial, in the middle of the patella, which is bypassed with a curvilinear movement to reach the underside of the patella. During final installation, the generator can be placed either in the abdominal region or on the lateral surface of the thigh (Figures F21 and F22).

RFP

Indication

- Refractory neuropathy of the saphenous nerve
- Neuroma of the branches of the saphenous nerve

Technique

After ultrasound identification of the nerve at the adductor canal as described above, it is possible to descend more distally to follow the infrapatellar branch. If correctly visualized, it probably signals a neuropathic disease of this branch, which is difficult to find it in a healthy subject. If necessary, a stimulation test confirms this, using the following parameters: 1 ms, 50 Hz, <0.45 V, after which radiofrequency is measured, setting the device to 2 ms at 45 V, with thermocouple temperature set at 42 °C. Sometimes, a neuroma is found on the nerve path. The procedure will be carried out identically but in direct contact with the neuroma, and over a longer period of time (Figure F23).

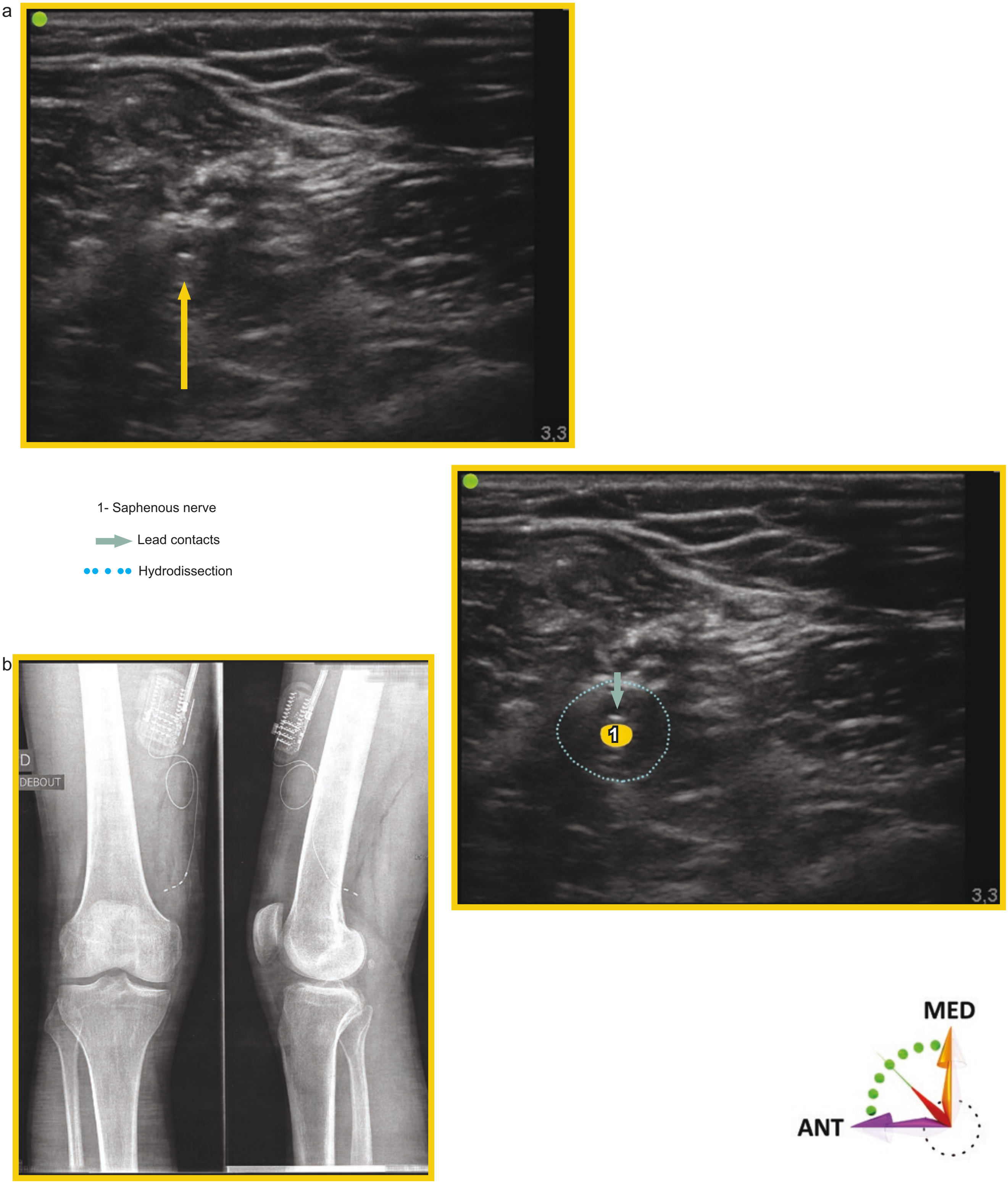
a
3,3
1- Saphenous nerve
Lead contacts
Hydrodissection
1
3,3
b
D
DEBOUT
MED
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Figure F21. Some illustrative views of a saphenous nerve stimulation. (**a**) Ultrasound guidance. (**b**) Post-op X-ray showing the lead positioning at the thigh distal third.

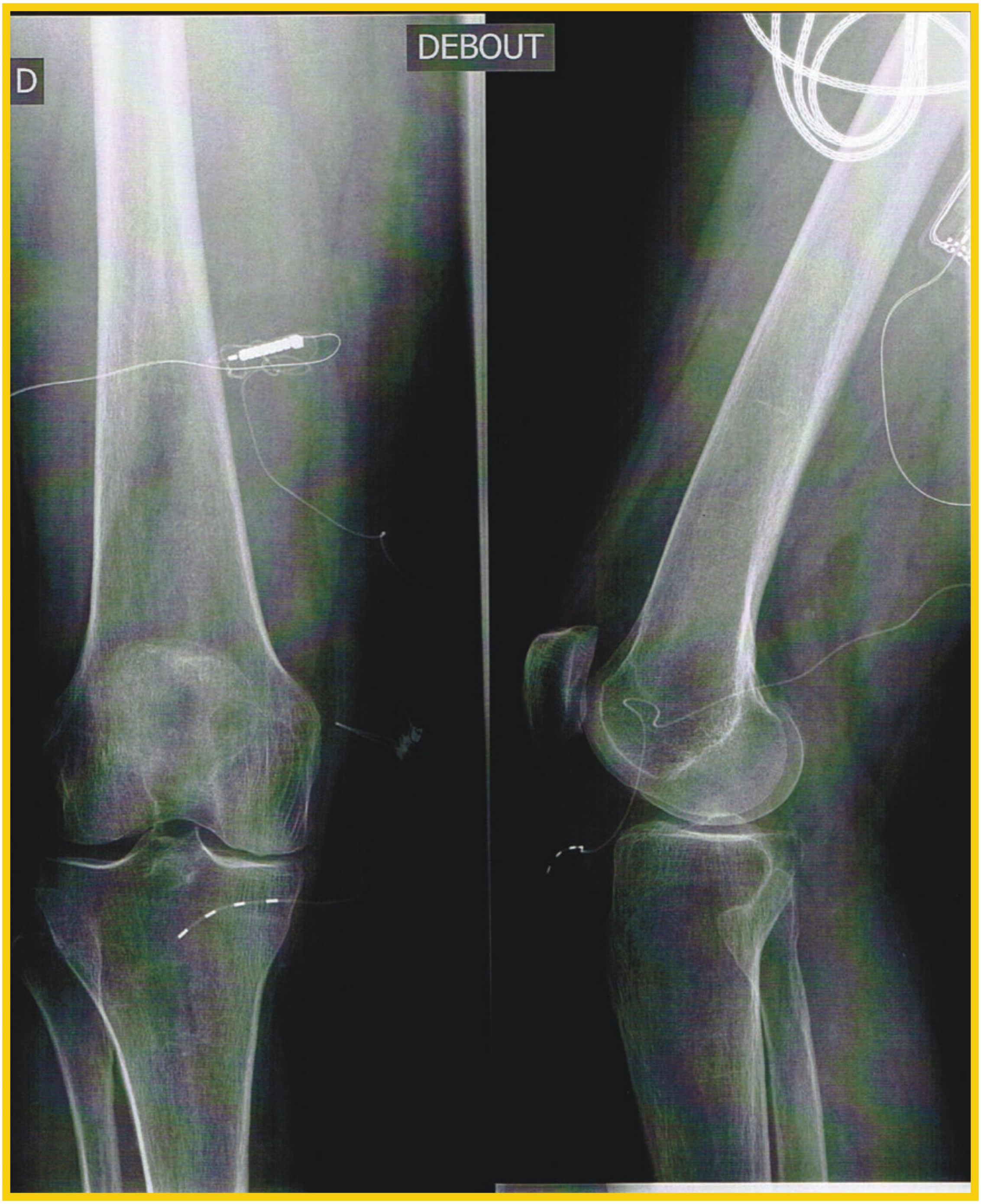
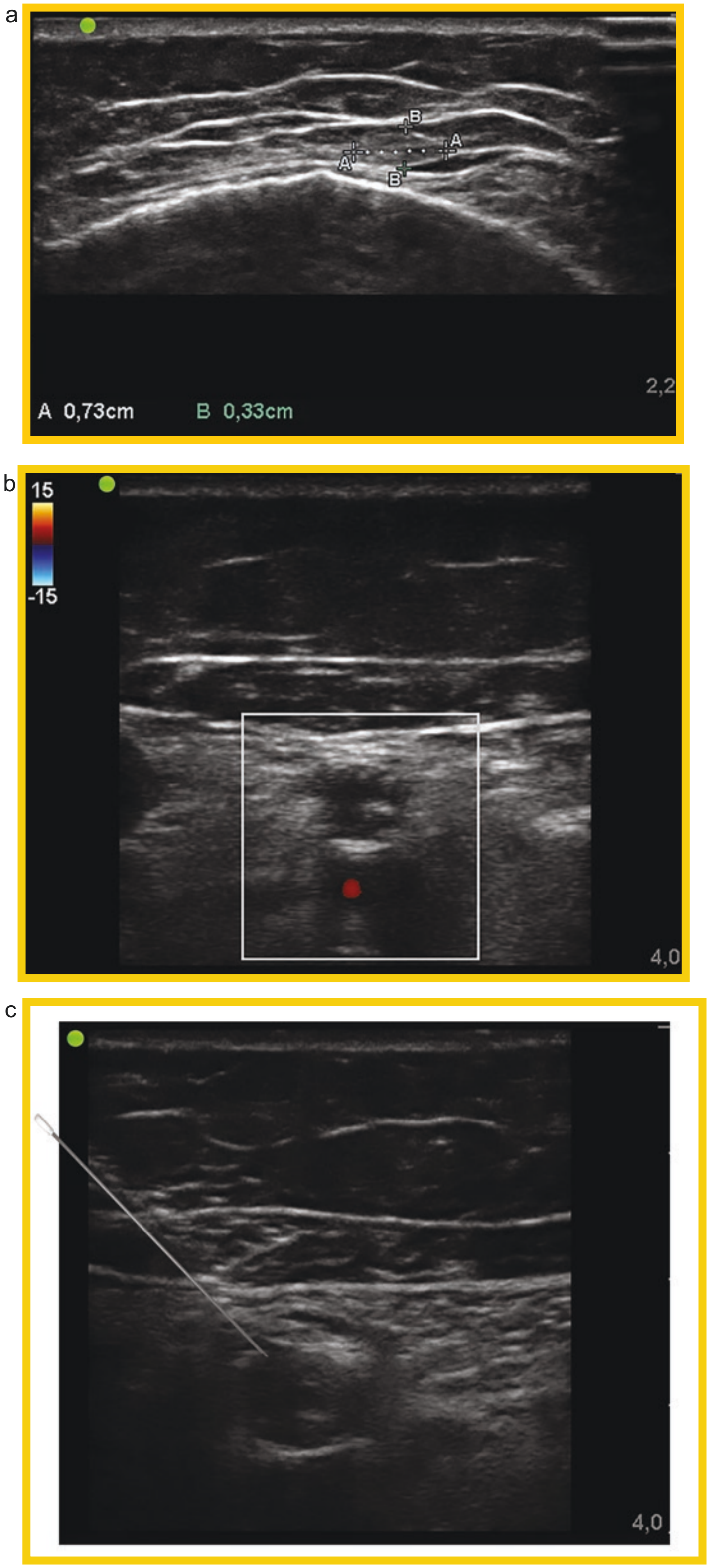


Figure F22. Post-op X-ray showing the lead positioning of an infrapatellar branch peripheral nerve stimulation.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A 0,73cm
B 0,33cm
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b
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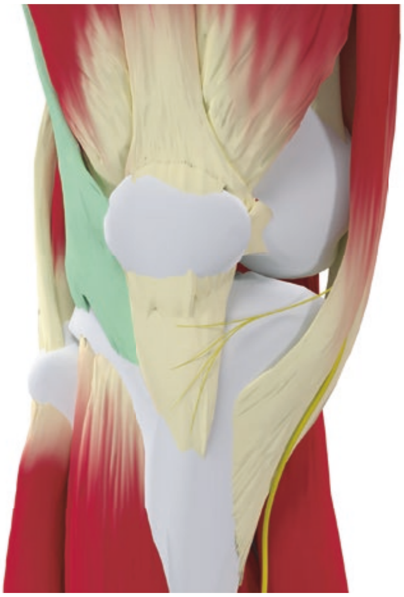
-15
4,0
c
4,0



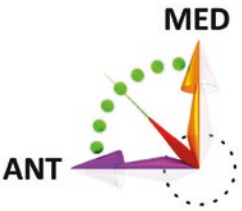


Figure F23. (**a**) Ultrasound transversal view showing a neuroma of the infrapatellar branch of the saphenous nerve. (**b**) Ultrasound transversal view showing a schwannoma of the saphenous nerve. Doppler mode view. (**c**) Pulsed radiofrequency on a saphenous nerve neuroma.

Surgical Procedure

Surgical Indications

- Injury to the femoral nerve by compression on a hematoma of the pectineus muscle, by stretching after hip surgery, by section after stabbing trauma.
- Neurotomy of the femoral nerve. It implicates the motor branches of the extra-pelvic femoral nerve intended for the rectus femoris muscle and the other three quadriceps leaders. It is rarely practiced. It is indicated especially in cases of spastic hip flexsum and more rarely in cases of spastic extension of the knee.

At the Femoral Trigone

Skin Incision

The main marker is located approximately three fingertips inside the anterior superior iliac spine at the iliopectineal arch. The incision is vertical, extending a little upwards to allow approach of the nerve at the intrapelvic level if necessary. It then descends to the thigh and uncovers the upper region of the femoral trigone (Figure F24).

Nervous Exposure

The thigh fascia is incised opposite the incision and under the iliopectineal arch to uncover the sartorius muscle within which the psoas muscle and its sheath are located. By receding the sartorius laterally, the femoral nerve gushes out of the arch outside the femoral artery. Further inside, we find the cribriform fascia and the saphenopopliteal junction flowing into the femoral vein, about 4 cm below the arch (Figure F25).

N.B.: If the nerve is exposed intrapelvically, it is necessary to ligate the deep circumflex iliac vessels, under the muscles of the anterolateral wall of the abdomen, which will then be pushed inwards, after being severed and uncoupled from the iliac crest.

Technical Pitfalls

- Damage to femoral vessels
- Peritoneal breach during nerve exposure in the intrapelvic region

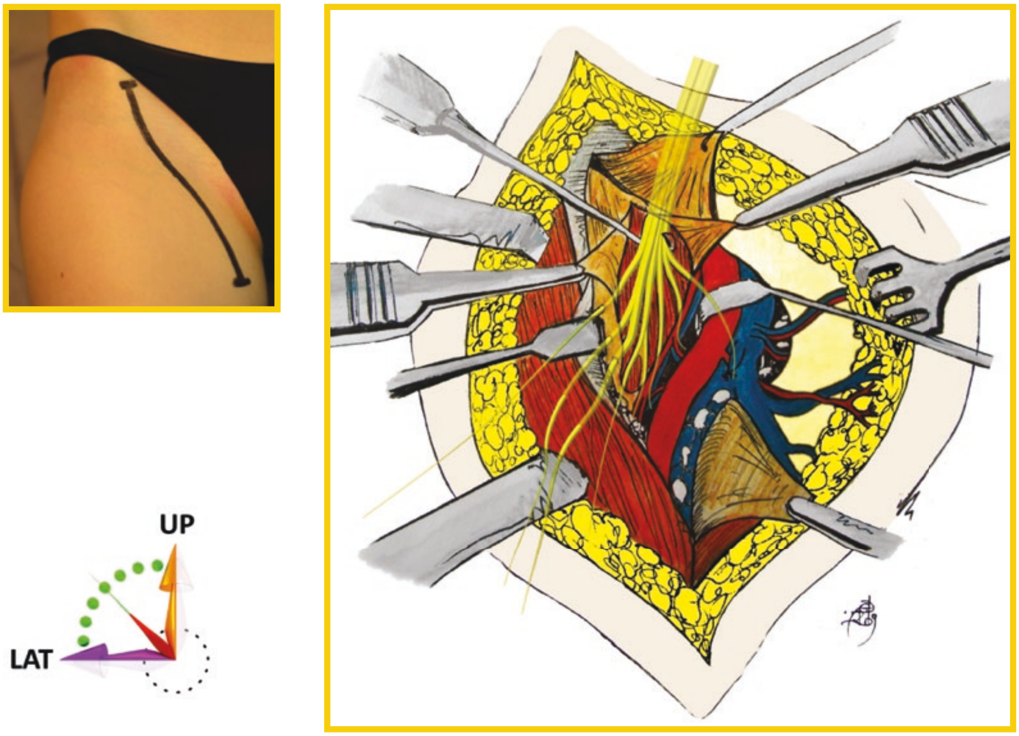
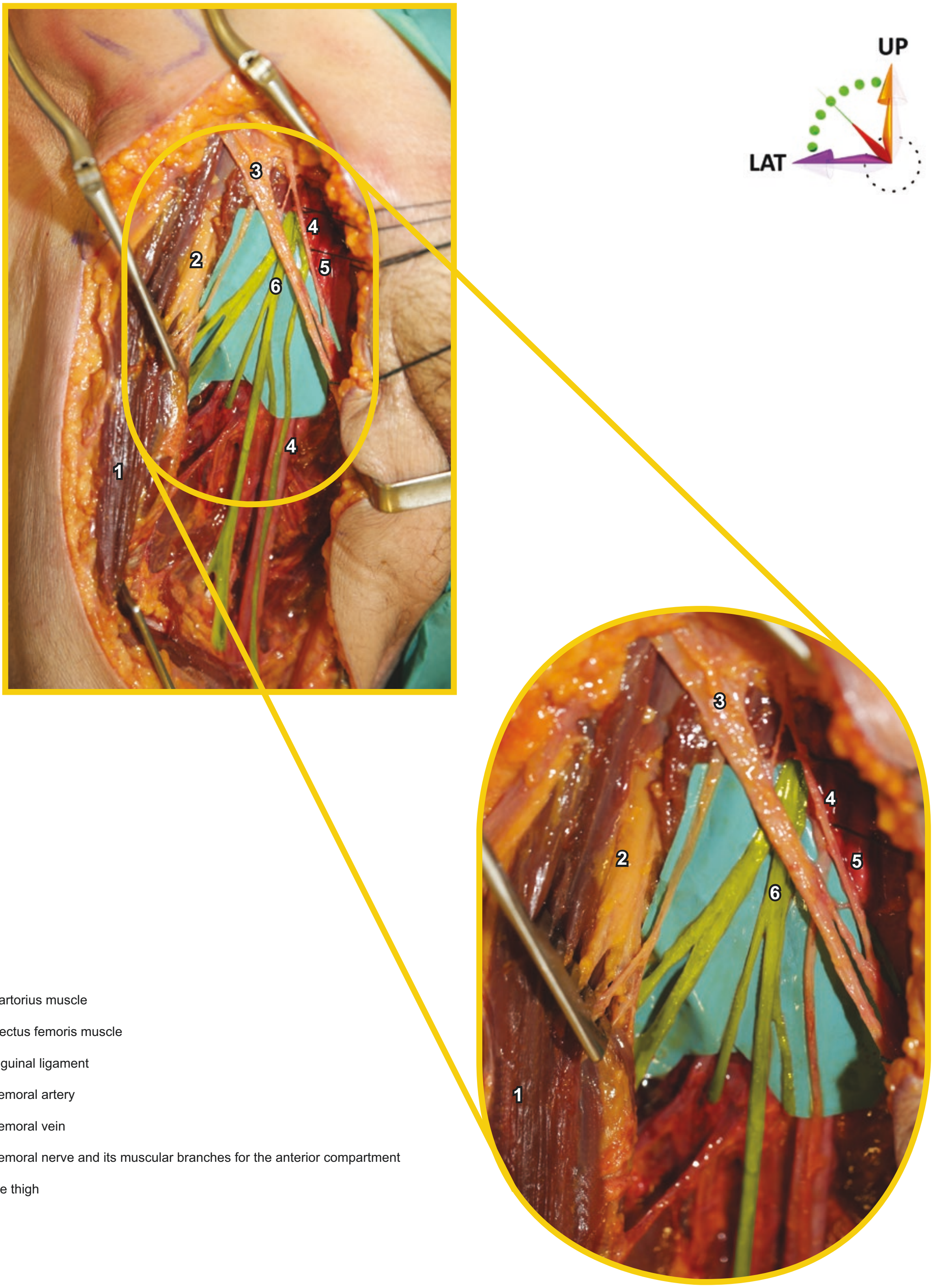


Figure F24. Surgical approach of the femoral nerve at the femoral triangle.



1- Sartorius muscle

2- Rectus femoris muscle

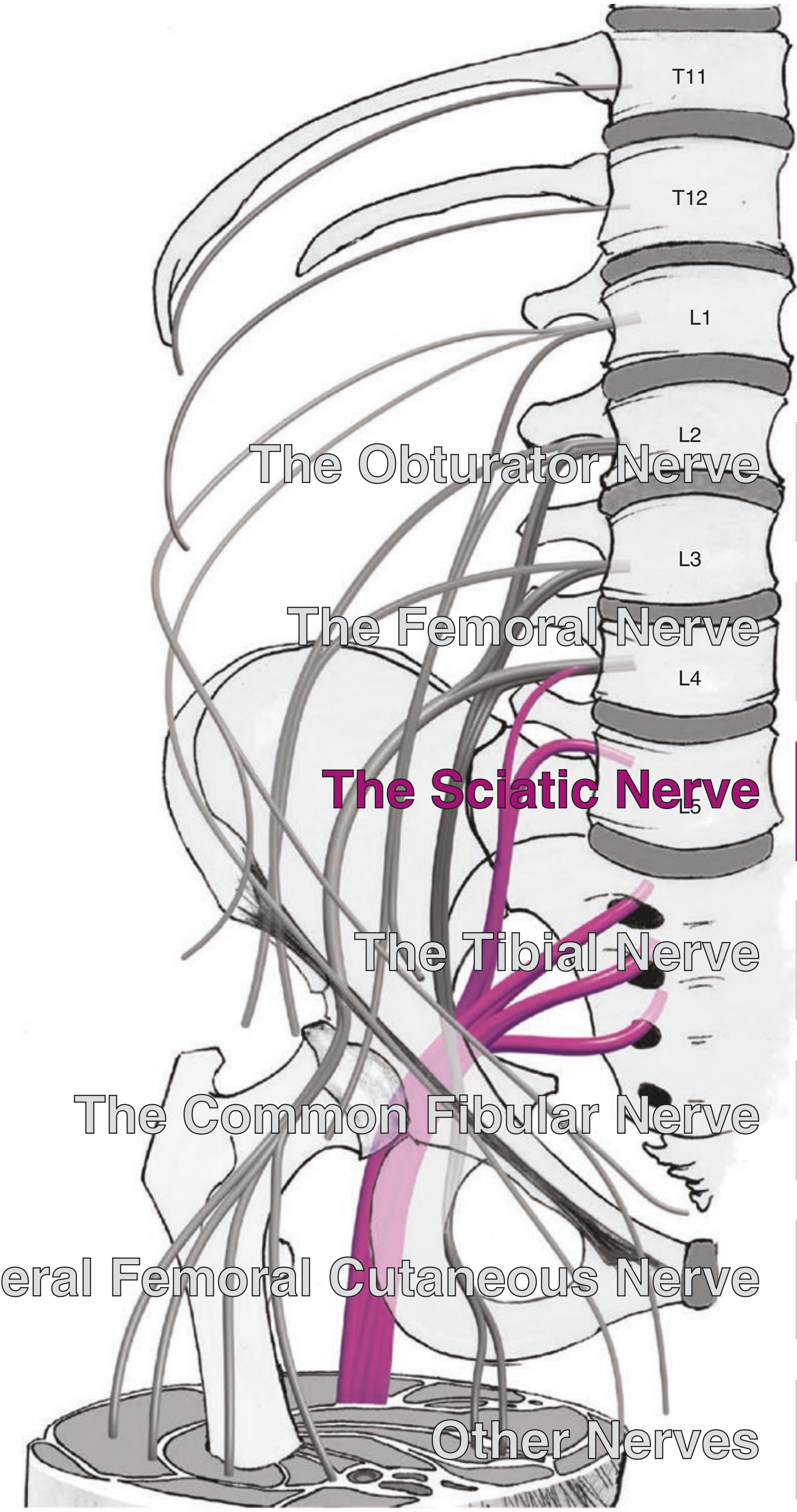
3- Inguinal ligament

4- Femoral artery

5- Femoral vein

6- Femoral nerve and its muscular branches for the anterior compartment of the thigh

Figure F25. Surgical approach of the femoral nerve at the femoral triangle.



The Obturator Nerve

The Femoral Nerve

The Sciatic Nerve

The Tibial Nerve

The Common Fibular Nerve

The Lateral Femoral Cutaneous Nerve

Other Nerves

Morphological Data

The sciatic nerve is a mixed nerve. It is the largest nerve in the human body. Its path is posterior to the root of the lower body, under the buttock, until the popliteal fossa, at which point it splits into two terminal branches: the tibial nerve and the common fibular nerve. The sciatic nerve trunk innervates the muscles of the posterior compartment of the thigh.

Origin

The sciatic nerve is the only terminal branch of the sacral plexus. It is composed of the L4, L5, S1, S2 and S3 roots (Figure Sc1). It comes from the lumbosacral trunk, formed by the anterior ramifications of the L4 and L5 roots and by the anterior ramifications of the first three sacral roots (Figure Sc2).

The lumbar roots unite in front of the sacroiliac joint, whilst the sacral roots unite in front of the piriformis muscle. The superior gluteal artery can be found between the lumbosacral trunk and the sacral roots. At its origin, the sciatic nerve faces the internal iliac vessels and the ureter in front.

Path

After its roots merge together, the sciatic nerve goes out through the great sciatic notch and under the piriformis muscle and continues its way on the posterior face of the buttock (Figures Sc3, Sc6, Sc9 and Sc15). Then, it describes a concave curve medially and goes down vertically in the posterior territory of the thigh, in its median axis in the top of the thigh. A little lower, it turns medially until the middle of the popliteal fossa, where it splits into its terminal branches (Figure Sc2).

It emerges at the level of the buttock, under the deep face of the piriformis muscle and above the superior gemellus muscle.

It is accompanied by the posterior femoral cutaneous nerve and by the posterior gluteal nerve behind, as well as the inferior rectal nerve, the obturator internus muscle and the internal pudendal pedicle medially. At this point, it faces the inferior gluteal artery medially (Figure Sc4). This artery gives off a collateral branch that follows the sciatic nerve and the accompanying artery of the sciatic nerve. The sciatic trunk goes between the greater trochanter on the outside and the ischial tuberosity on the inside.

The landmark to access the nerve in the thigh is a vertical line drawn by taking a point halfway between the ischial tuberosity and the greater trochanter at the top and another point at the top of the diamond formed by the popliteal fossa at the bottom.

It is covered at the level of the buttock by the gluteus maximus muscle. In this area, the nerve goes behind the adductor magnus muscle. It then goes between the two heads of the biceps femoris muscle, with the short head in front and the long head behind (Figure Sc5). It then faces the two heads of this muscle laterally and the semitendinosus and semimembranosus muscles medially. The artery of the sciatic nerve follows the nerve in its path in the thigh, lying on its posterior side.

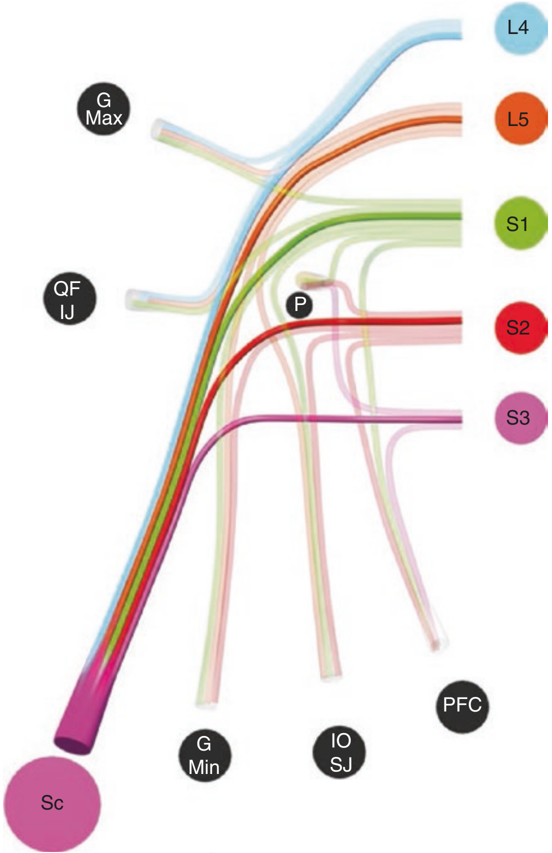


Figure Sc1. Origin of the sciatic nerve.

Electronic Supplementary Material The online version of this chapter (https://doi.org/10.1007/978-3-030-49179-6_15) contains supplementary material, which is available to authorized users.

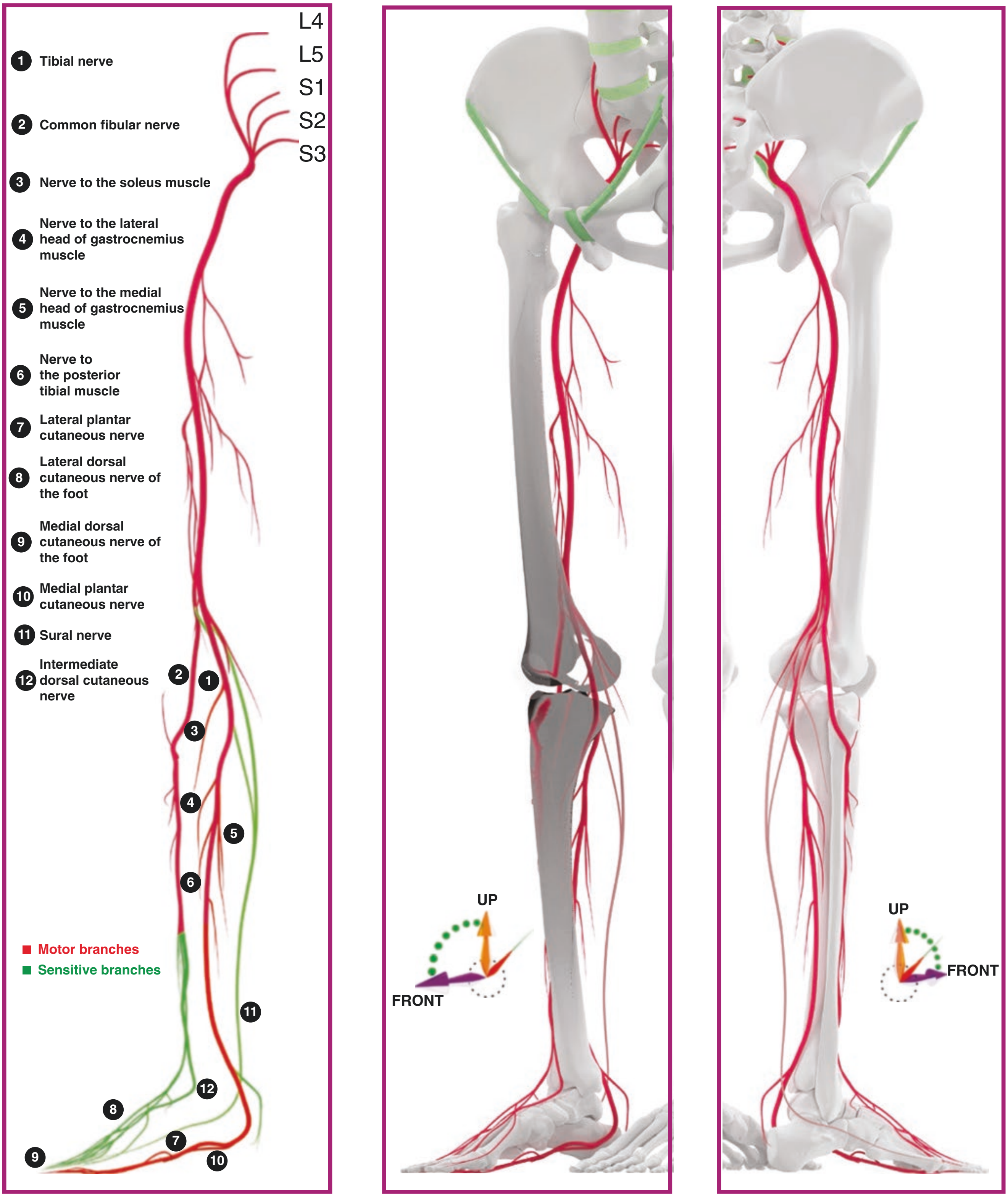

L4
L5
S1
S2
S3
① Tibial nerve
② Common fibular nerve
③ Nerve to the soleus muscle
④ Nerve to the lateral head of gastrocnemius muscle
⑤ Nerve to the medial head of gastrocnemius muscle
⑥ Nerve to the posterior tibial muscle
⑦ Lateral plantar cutaneous nerve
⑧ Lateral dorsal cutaneous nerve of the foot
⑨ Medial dorsal cutaneous nerve of the foot
⑩ Medial plantar cutaneous nerve
⑪ Sural nerve
⑫ Intermediate dorsal cutaneous nerve
②
①
③
④
⑤
⑥
🟥 Motor branches
🟩 Sensitive branches
⑪
⑫
⑧
⑦
⑨
⑩
UP
FRONT
UP
FRONT

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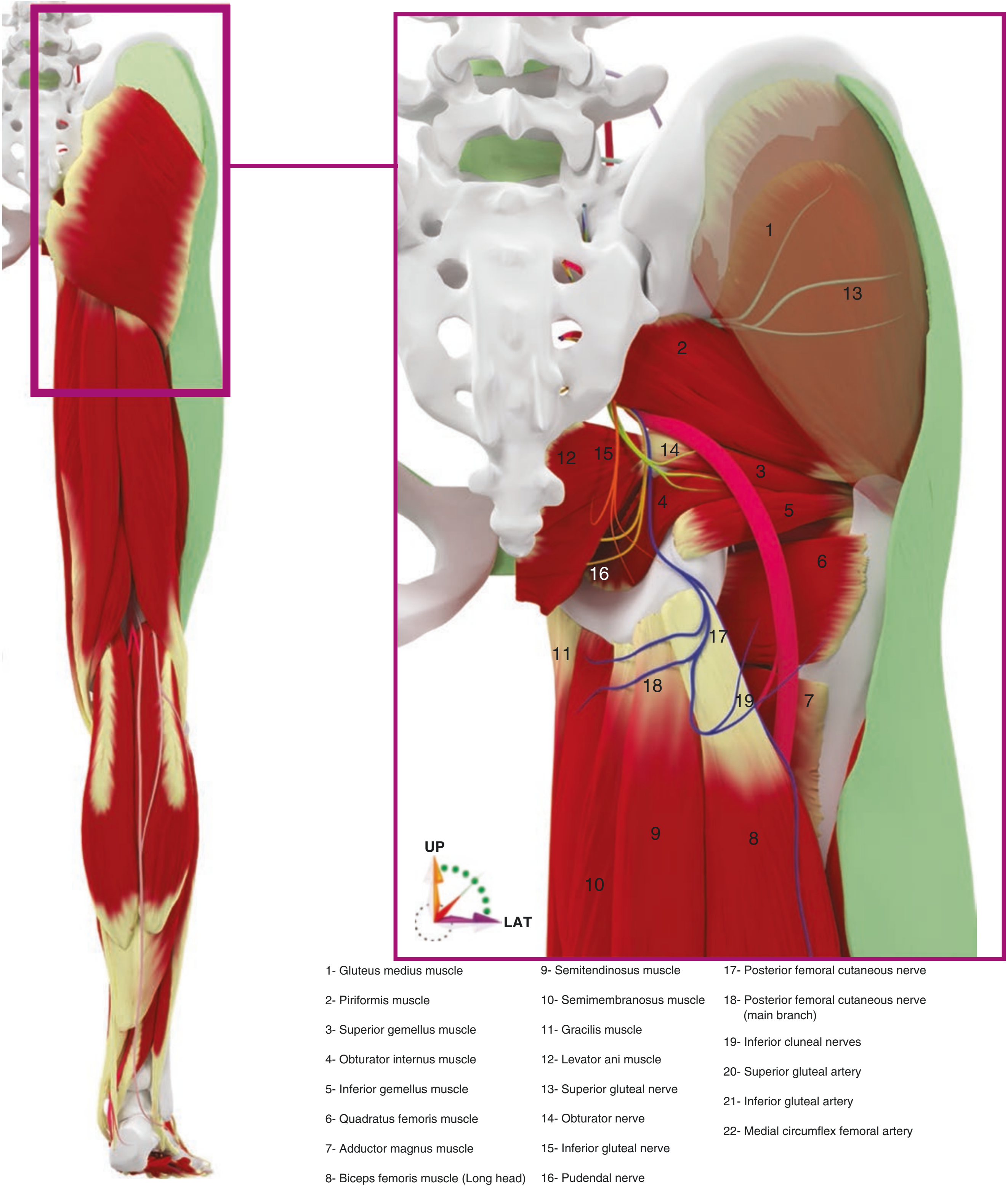
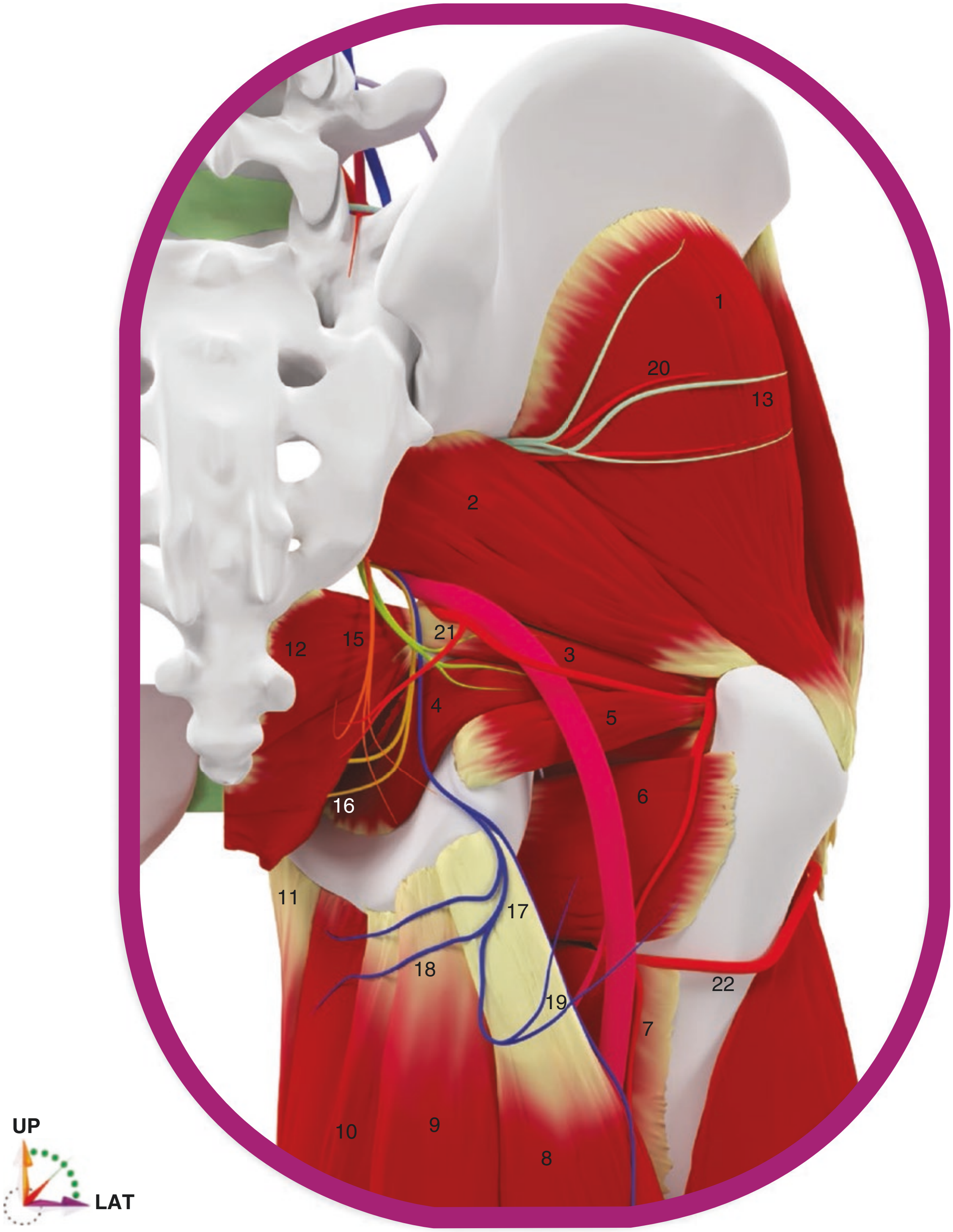
Figure Sc2. Topographical distribution of the collateral and terminal branches of the sciatic nerve and their relations with bones.



1- Gluteus medius muscle
2- Piriformis muscle
3- Superior gemellus muscle
4- Obturator internus muscle
5- Inferior gemellus muscle
6- Quadratus femoris muscle
7- Adductor magnus muscle
8- Biceps femoris muscle (Long head)
9- Semitendinosus muscle
10- Semimembranosus muscle
11- Gracilis muscle
12- Levator ani muscle
13- Superior gluteal nerve
14- Obturator nerve
15- Inferior gluteal nerve
16- Pudendal nerve
17- Posterior femoral cutaneous nerve
18- Posterior femoral cutaneous nerve (main branch)
19- Inferior cluneal nerves
20- Superior gluteal artery
21- Inferior gluteal artery
22- Medial circumflex femoral artery

Figure Sc3. Muscular relations of the sciatic nerve and its collateral branches in the buttock.


1
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12
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8
UP
LAT

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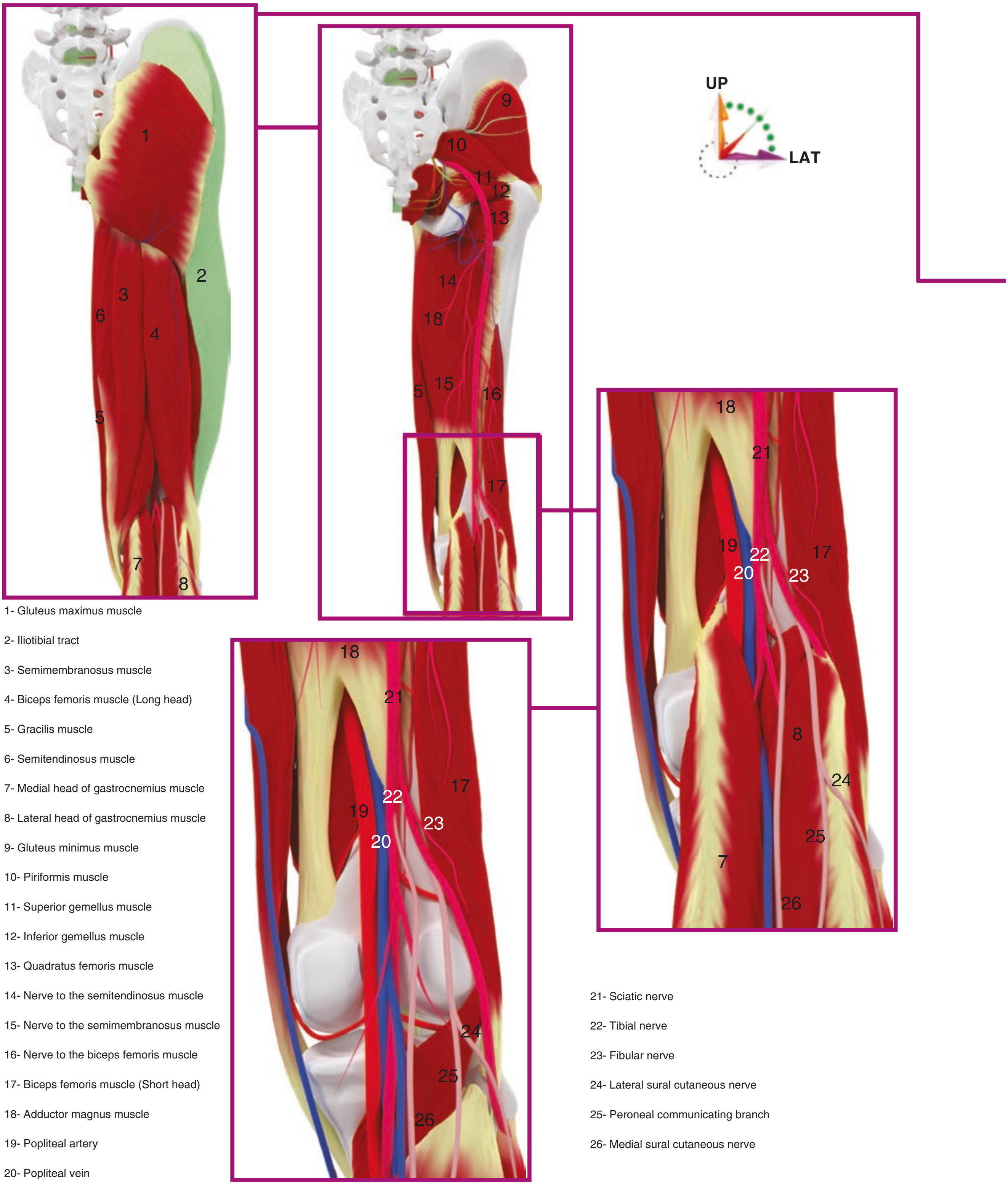
Figure Sc4. Neurovascular relations of the sciatic nerve collateral branches and trunk in the buttock.

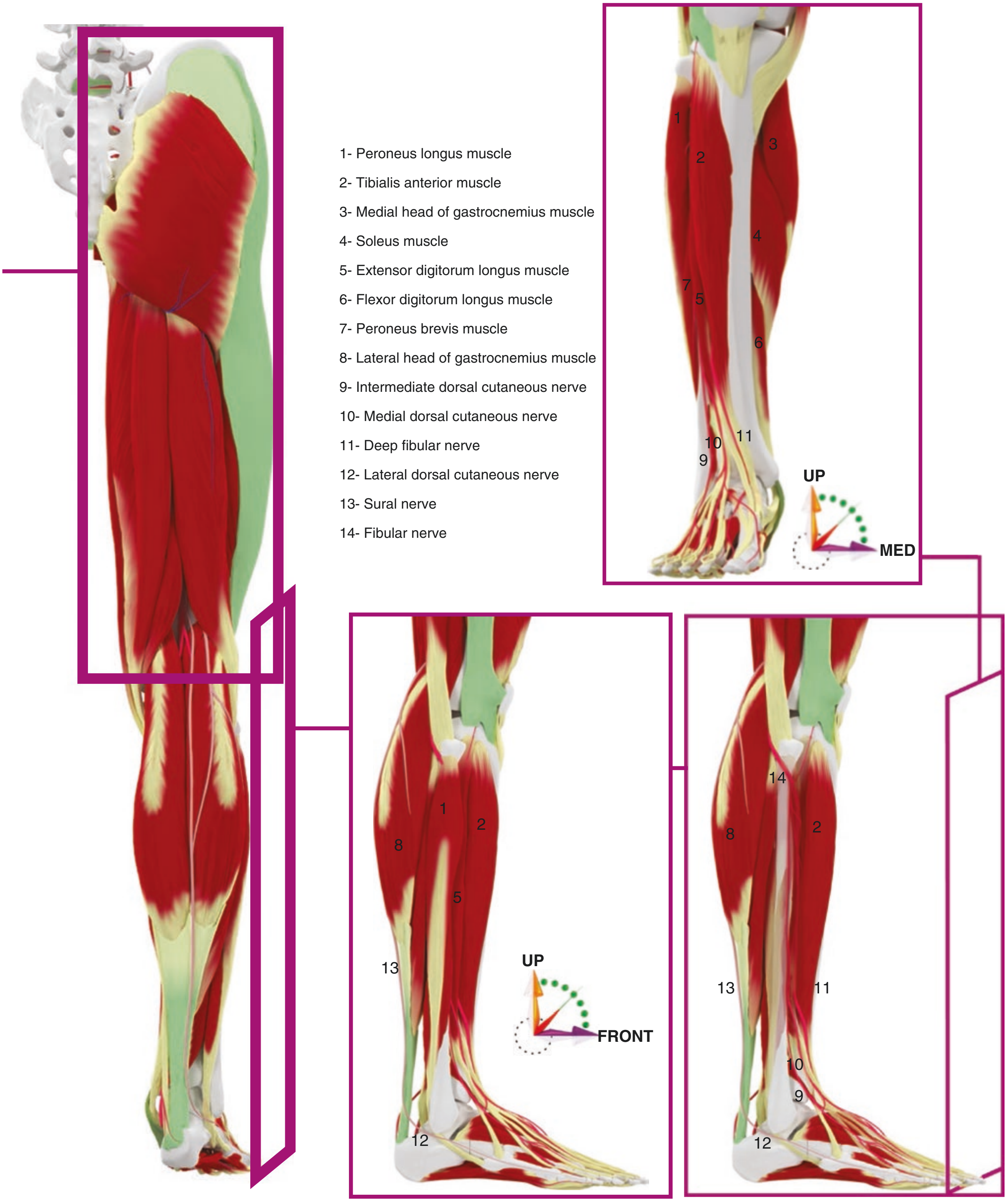
The Sciatic Nerve



1- Gluteus maximus muscle
2- Iliotibial tract
3- Semimembranosus muscle
4- Biceps femoris muscle (Long head)
5- Gracilis muscle
6- Semitendinosus muscle
7- Medial head of gastrocnemius muscle
8- Lateral head of gastrocnemius muscle
9- Gluteus minimus muscle
10- Piriformis muscle
11- Superior gemellus muscle
12- Inferior gemellus muscle
13- Quadratus femoris muscle
14- Nerve to the semitendinosus muscle
15- Nerve to the semimembranosus muscle
16- Nerve to the biceps femoris muscle
17- Biceps femoris muscle (Short head)
18- Adductor magnus muscle
19- Popliteal artery
20- Popliteal vein

21- Sciatic nerve
22- Tibial nerve
23- Fibular nerve
24- Lateral sural cutaneous nerve
25- Peroneal communicating branch
26- Medial sural cutaneous nerve

Figure Sc5. Muscular relations of the sciatic nerve in the thigh and in the popliteal fossa.



1- Peroneus longus muscle
2- Tibialis anterior muscle
3- Medial head of gastrocnemius muscle
4- Soleus muscle
5- Extensor digitorum longus muscle
6- Flexor digitorum longus muscle
7- Peroneus brevis muscle
8- Lateral head of gastrocnemius muscle
9- Intermediate dorsal cutaneous nerve
10- Medial dorsal cutaneous nerve
11- Deep fibular nerve
12- Lateral dorsal cutaneous nerve
13- Sural nerve
14- Fibular nerve

Figure Sc6. Muscular relations of the sciatic nerve in the leg (lateral and anterior views).

Finally, it passes above the heads of the gastrocnemius muscle, in the median axis of the popliteal fossa, where it gives off its terminal branches (Figure Sc5). In its terminal part, the sciatic nerve is accompanied by the femoral artery, which generally splits a few centimetres above the nerve division.

Neurovascular Relations

At its origin, the sciatic nerve faces the internal iliac artery in front.

In the buttock, the sciatic nerve faces (Figures Sc3 and Sc4):

- The superior gluteal artery and nerves via the piriformis muscle above
- The inferior gluteal artery medially (formerly called sciatic artery) which then crosses the sciatic nerve in behind

In the thigh, the sciatic nerve is escorted by the accompanying artery of the sciatic nerve, which is a branch of the inferior gluteal artery (Figure Sc5).

At its terminal part, the nerve faces the popliteal artery medially, which passes under the adductor hiatus (Figures Sc10 and Sc11).

Collateral Branches

The sciatic nerve gives off many motor branches for the muscles of the posterior compartment of the thigh (Figure Sc5):

- The superior and inferior nerves of the semitendinosus muscle
- The nerve of the semimembranosus muscle, which it penetrates on its lateral side
- The nerve of the adductor magnus muscle
- A branch for each head of the biceps femoris muscle

And finally, an articular nerve for the posterior face of the knee joint.

Terminal Branches

In the popliteal fossa, the sciatic nerve splits into two terminal branches, the tibial nerve medially and the common fibular nerve laterally (Figures Sc9, Sc12, and Sc13).

Motor Function

The sciatic nerve innervates the muscles of the posterior compartment of the thigh: the biceps femoris, semitendinosus, and semimembranosus and adductor magnus muscles (Figure Sc7).

It therefore takes charge of the flexion of the leg on the thigh and of the extension of the thigh on the buttock.

Through its terminal branches, it also takes charge of a large part of movements such as propulsion, stabilisation and dorsiflexion as well as foot inclination.

Sensitive Function

The sciatic nerve does not have its own sensitive territory. Its terminal branches take charge of the cutaneous innervation of the foot and of the lateral part of the leg (Figure Sc7). The tibial crest therefore represents the limit between these cutaneous territories and that of the saphenous nerve, in the medial part of the leg.

Anastomoses

The sciatic nerve makes anastomoses in its proximal part with the posterior femoral cutaneous nerve, at the beginning of its path outside of the pelvis.

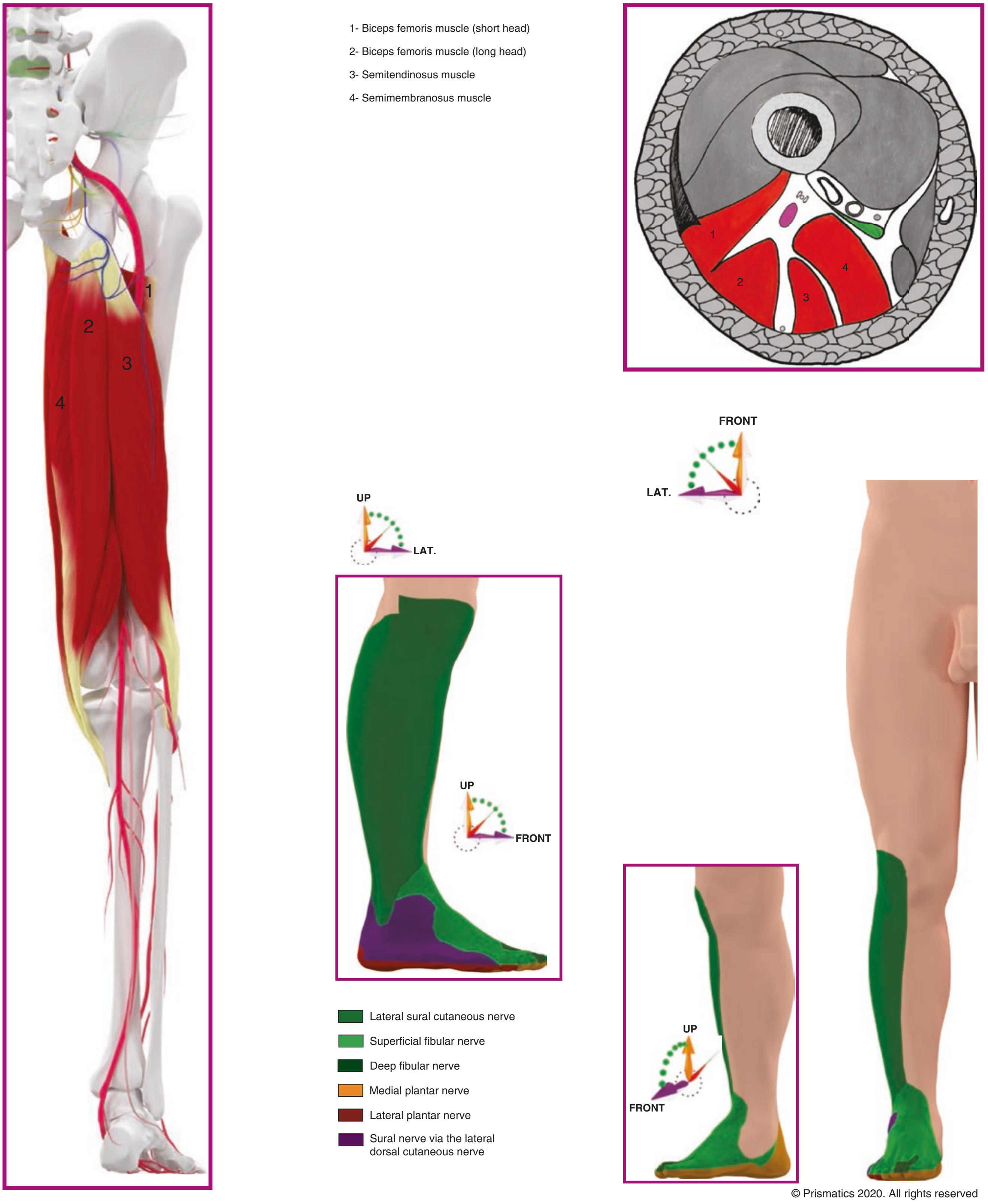

1- Biceps femoris muscle (short head)
2- Biceps femoris muscle (long head)
3- Semitendinosus muscle
4- Semimembranosus muscle
1
2
3
4
FRONT
LAT.
UP
LAT.
UP
FRONT
UP
FRONT
🟩 Lateral sural cutaneous nerve
🟩 Superficial fibular nerve
🟩 Deep fibular nerve
🟧 Medial plantar nerve
🟥 Lateral plantar nerve
🟪 Sural nerve via the lateral dorsal cutaneous nerve

Figure Sc7. Motor and sensitive innervation of the sciatic nerve. Motor innervation of the sciatic nerve.

The Sciatic Nerve

1- Lateral femoral cutaneous nerve

2- Anterior cutaneous nerve of the thigh

3- Medial cutaneous nerve of the thigh

4- Nerve to the quadriceps muscle

5- Terminal branch of the femoral nerve

6- Branch of the obturator nerve

7- Sciatic nerve

8- Inferior cluneal nerves

9- Saphenous nerve

10- Posterior femoral cutaneous nerve

11- Great saphenous vein

12- Artery to the quadriceps muscle

13- Deep femoral artery and vein

14- Femoral artery and vein

15- Inferior gluteal artery

16- Deep branch of the deep femoral artery

17- Tensor fasciae latae muscle

18- Rectus femoris muscle

19- Sartorius muscle

20- Adductor longus muscle

21- Vastus lateralis muscle

22- Vastus intermedius muscle

23- Vastus medialis muscle

24- Pectineus muscle

25- Adductor brevis muscle

26- Gracilis muscle

27- Adductor magnus muscle

28- Semimembranosus muscle

29- Long head of the biceps femoris muscle

30- Semitendinosus muscle

31- Gluteus maximus muscle

32- Short head of the biceps femoris muscle

33- Femur

34- Obturator nerve (articular branch to the knee joint)

35- Obturator nerve (cutaneous branch)

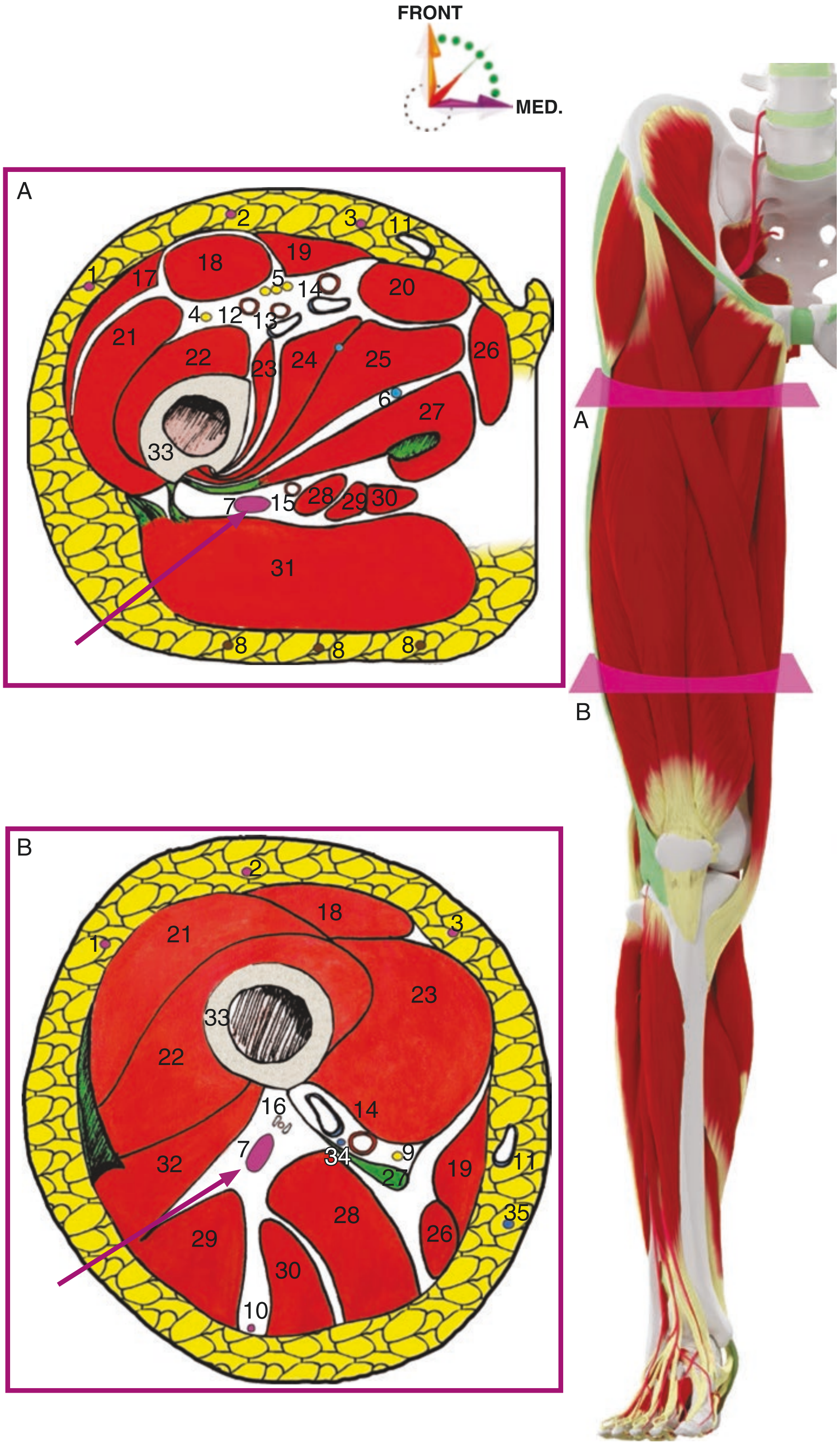
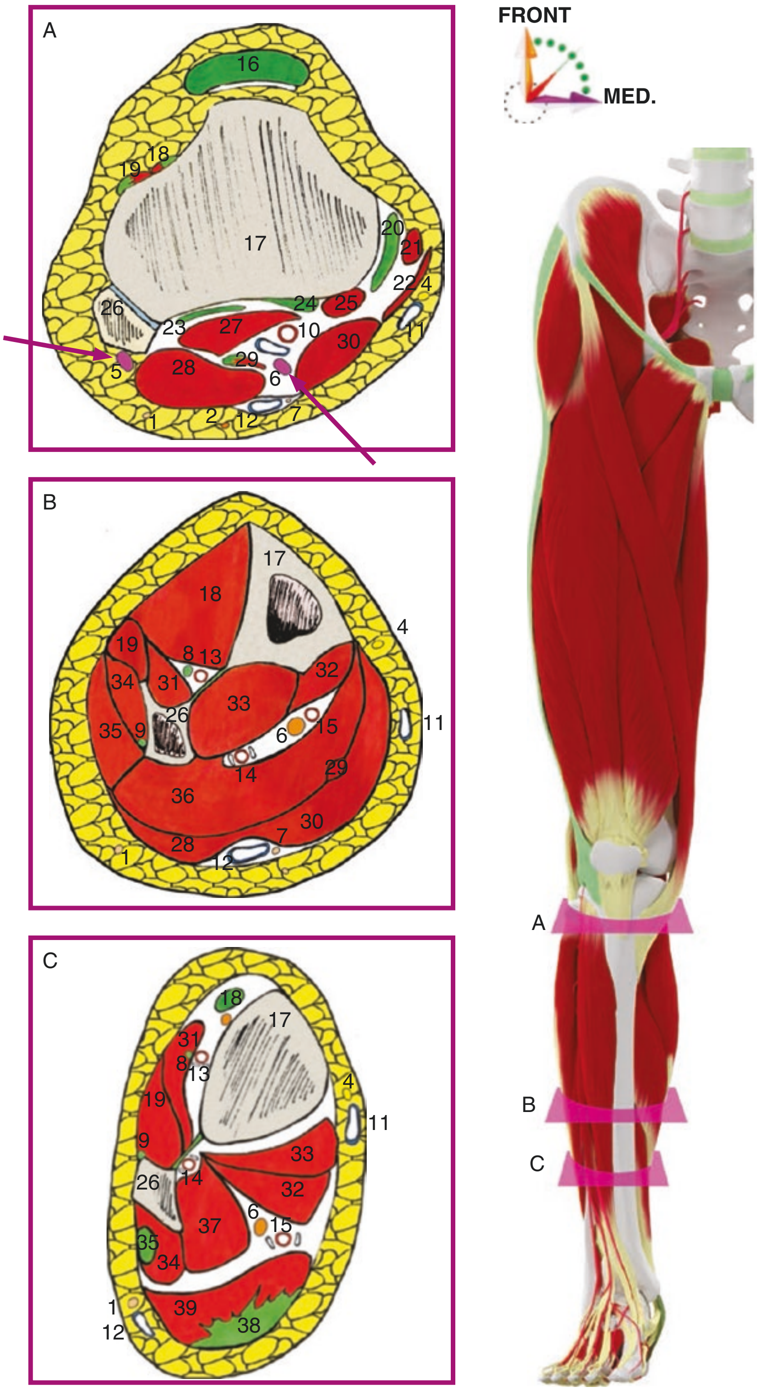


Figure Sc8. Relations of the sciatic nerve in the thigh, axial sections.

1- Lateral sural cutaneous nerve
2- Peroneal communicating nerve
3- Medial sural cutaneous nerve
4- Saphenous nerve
5- Fibular nerve
6- Tibial nerve
7- Sural nerve
8- Deep fibular nerve
9- Superficial fibular nerve
10- Popliteal artery and vein
11- Great saphenous vein
12- Small saphenous vein
13- Anterior tibial artery
14- Fibular artery and vein
15- Posterior tibial artery
16- Patellar ligament of quadriceps femoris muscle
17- Tibia
18- Tibialis anterior muscle
19- Extensor digitorum longus muscle
20- Medial collateral ligament
21- Gracilis muscle
22- Sartorius muscle
23- Synovial bursa
24- Posterior cruciate ligament
25- Semimembranosus muscle
26- Fibula
27- Popliteus muscle
28- Lateral head of the gastrocnemius muscle
29- Plantaris muscle
30- Medial head of the gastrocnemius muscle
31- Extensor hallucis longus muscle
32- Flexor digitorum longus muscle
33- Posterior tibial muscle
34- Peroneus brevis muscle
35- Peroneus longus muscle
36- Soleus muscle
37- Flexor hallucis longus muscle
38- Calcaneal tendon
39- Triceps surae muscle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26
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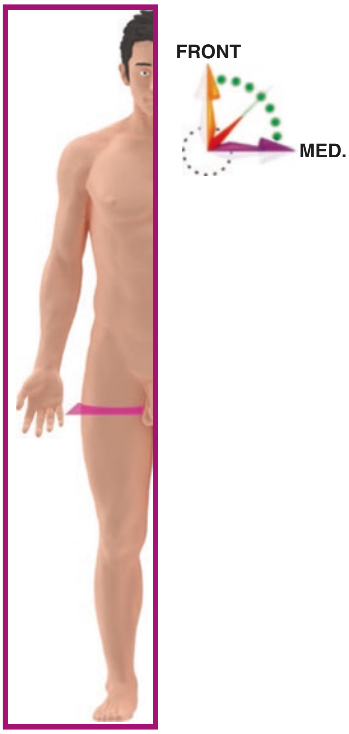
Figure Sc9. Relations of the sciatic nerve in the leg, axial section.

The Sciatic Nerve



1- Vastus lateralis muscle

2- Vastus intermedius muscle

3- Tensor fasciae latae muscle

4- Vastus medialis muscle

5- Rectus femoris muscle

6- Sartorius muscle

7- Femur

8- Femoral artery and vein

9- Femoral nerve

10- Deep femoral artery and vein

11- Adductor longus muscle

12- Gracilis muscle

13- Adductor brevis muscle

14- Adductor magnus muscle

15- Semimembranosus muscle

16- Sciatic nerve

17- Anterior branch of the obturator nerve

18- Posterior branch of the obturator nerve

19- Tendon of the biceps femoris muscle

20- Tendon of the semitendinosus muscle

21- Gluteus maximus muscle

22- Pectineus muscle

23- Lateral femoral cutaneous nerve

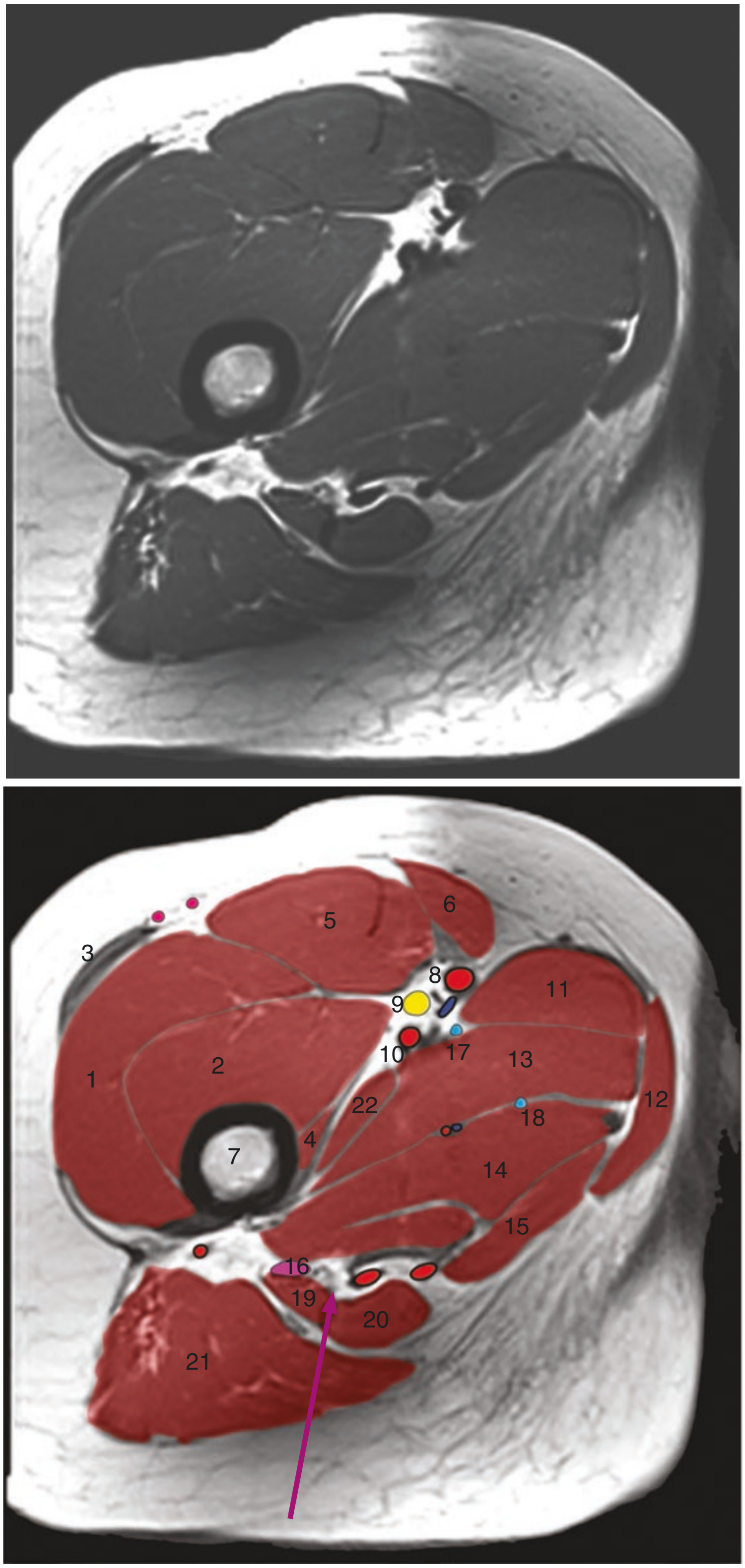
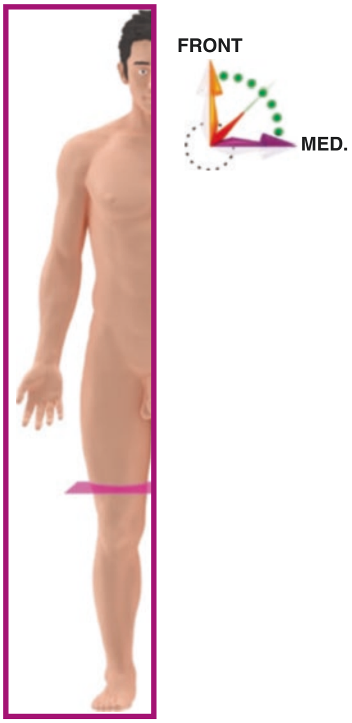
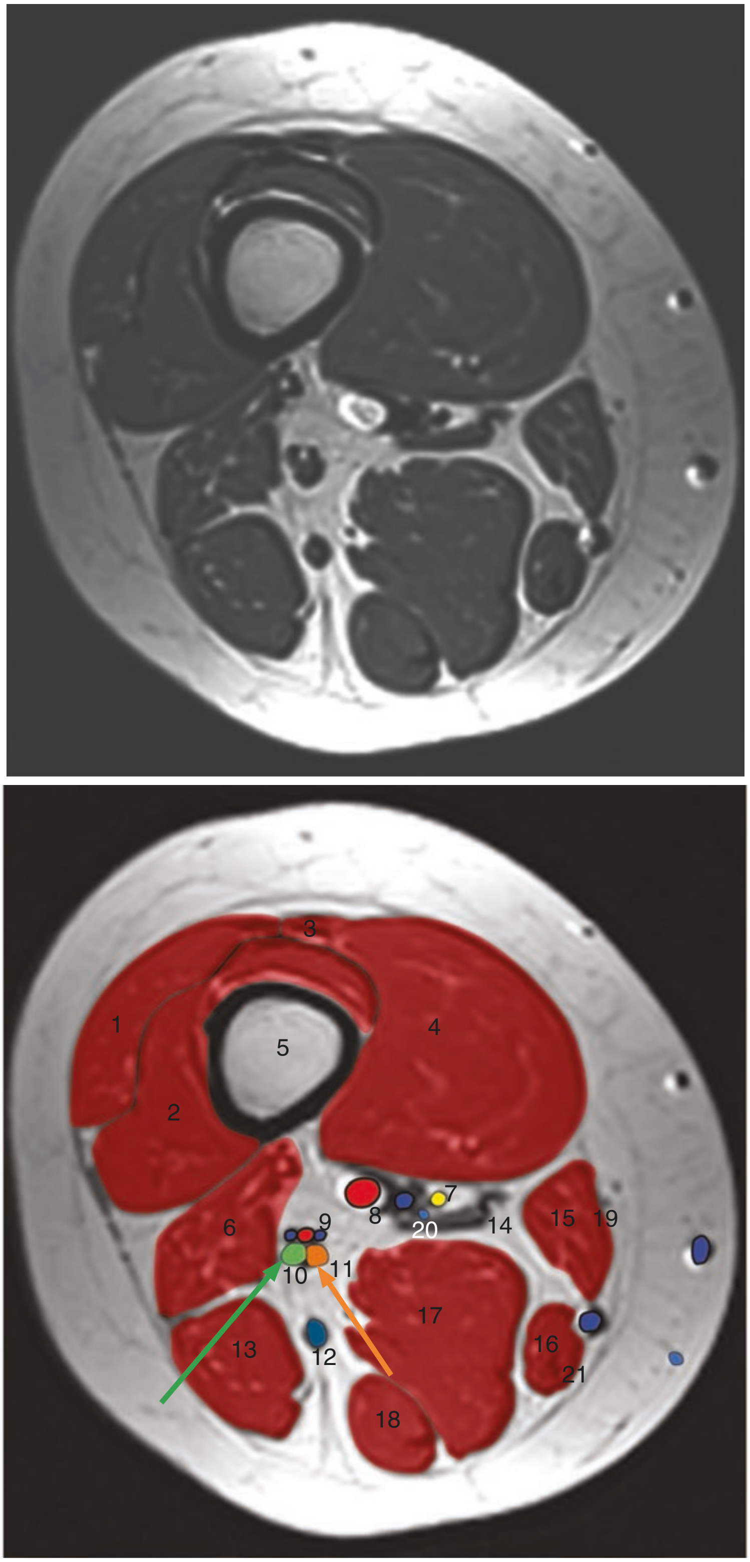


Figure Sc10. MRI scans at the proximal third of the thigh through the sciatic nerve and its terminal branches.





1- Vastus lateralis muscle

2- Vastus intermedius muscle

3- Rectus femoris muscle

4- Vastus medialis muscle

5- Femur

6- Short head of the biceps femoris muscle

7- Saphenous nerve

8- Femoral artery and vein

9- Perforating artery and vein of the deep femoral artery and vein

10- Common fibular nerve

11- Tibial nerve

12- Posterior femoral cutaneous nerve

13- Long head of the biceps femoris muscle

14- Adductor magnus muscle

15- Sartorius muscle

16- Gracilis muscle

17- Semimembranosus muscle

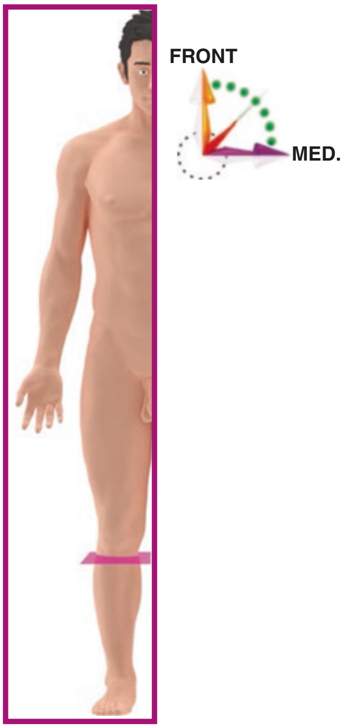
18- Semitendinosus muscle

19- Great saphenous vein

20- Obturator nerve (articular branch to the knee joint)

21- Obturator nerve (cutaneous branch)

Figure Sc11. MRI scans at the distal third of the thigh through the sciatic nerve and its terminal branches.



1- Patellar ligament
2- Deep infrapatellar bursa
3- Tibia
4- Fibula
5- Popliteus muscle
6- Common fibular nerve
7- Posterior tibial artery and vein
8- Tibial nerve
9- Great saphenous vein
10- Soleus muscle
11- Lateral head of gastrocnemius muscle
12- Medial head of gastrocnemius muscle

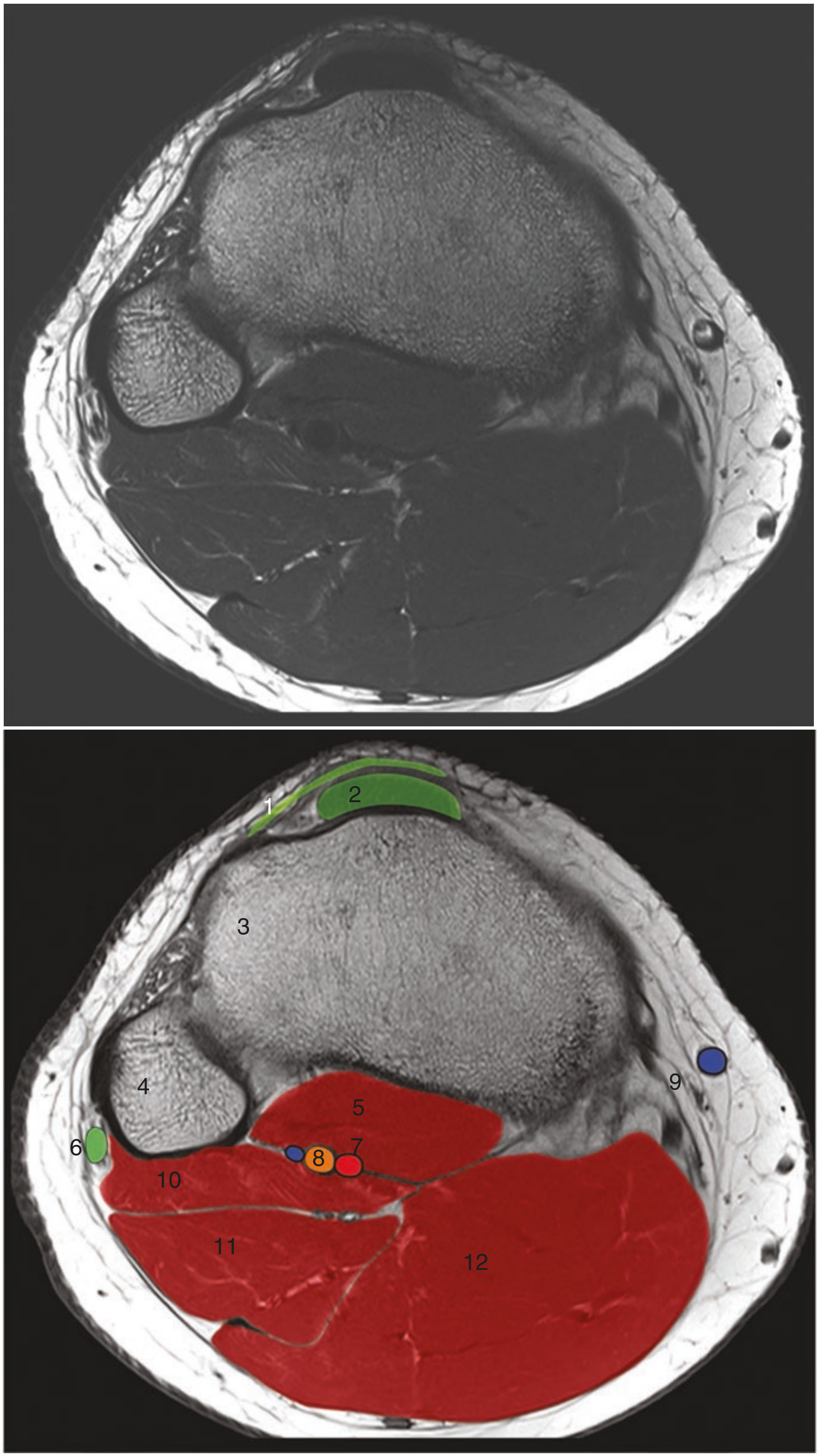
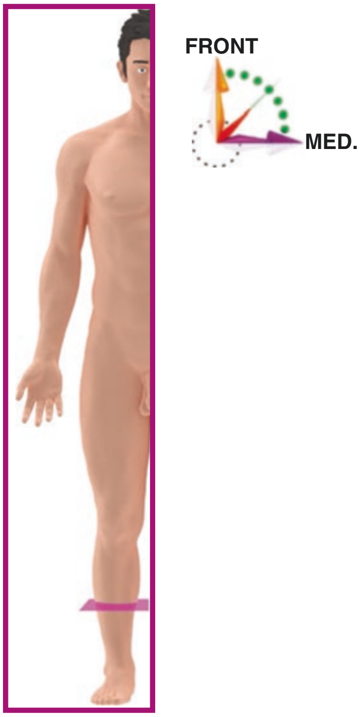


Figure Sc12. MRI scans at the proximal third of the leg through the sciatic nerve and its terminal branches.



1- Extensor digitorum longus muscle
2- Tibialis anterior muscle
3- Tibia
4- Flexor digitorum longus muscle
5- Deep fibular nerve
6- Anterior tibial artery and vein
7- Great saphenous vein
8- Peroneus longus and brevis muscles
9- Fibula
10- Posterior tibial muscle
11- Posterior tibial artery and vein
12- Tibial nerve
13- Flexor hallucis longus muscle
14- Lateral head of gastrocnemius muscle
15- Medial head of gastrocnemius muscle
16- Small saphenous vein
17- Medial sural cutaneous nerve
18- Sural nerve
19- Soleus muscle
20- Extensor hallucis longus muscle

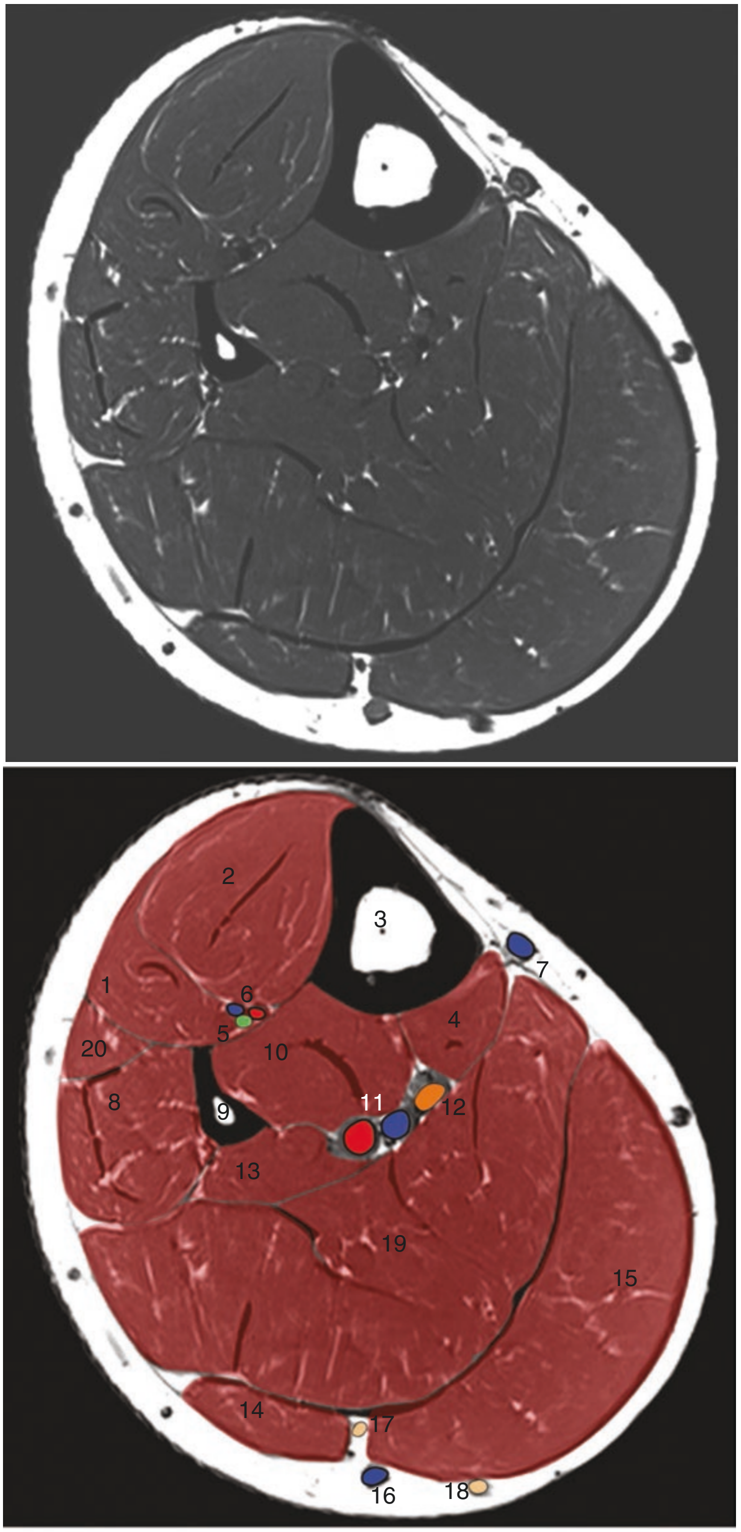
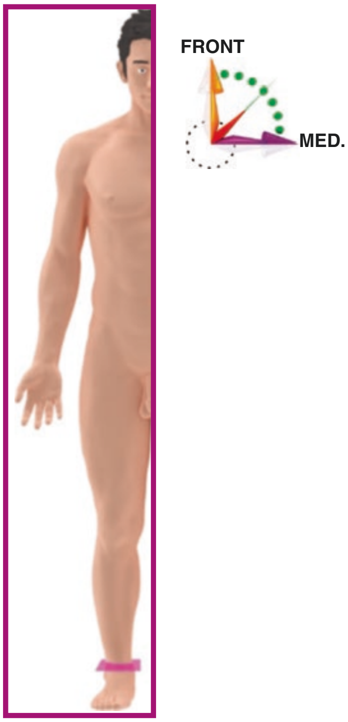
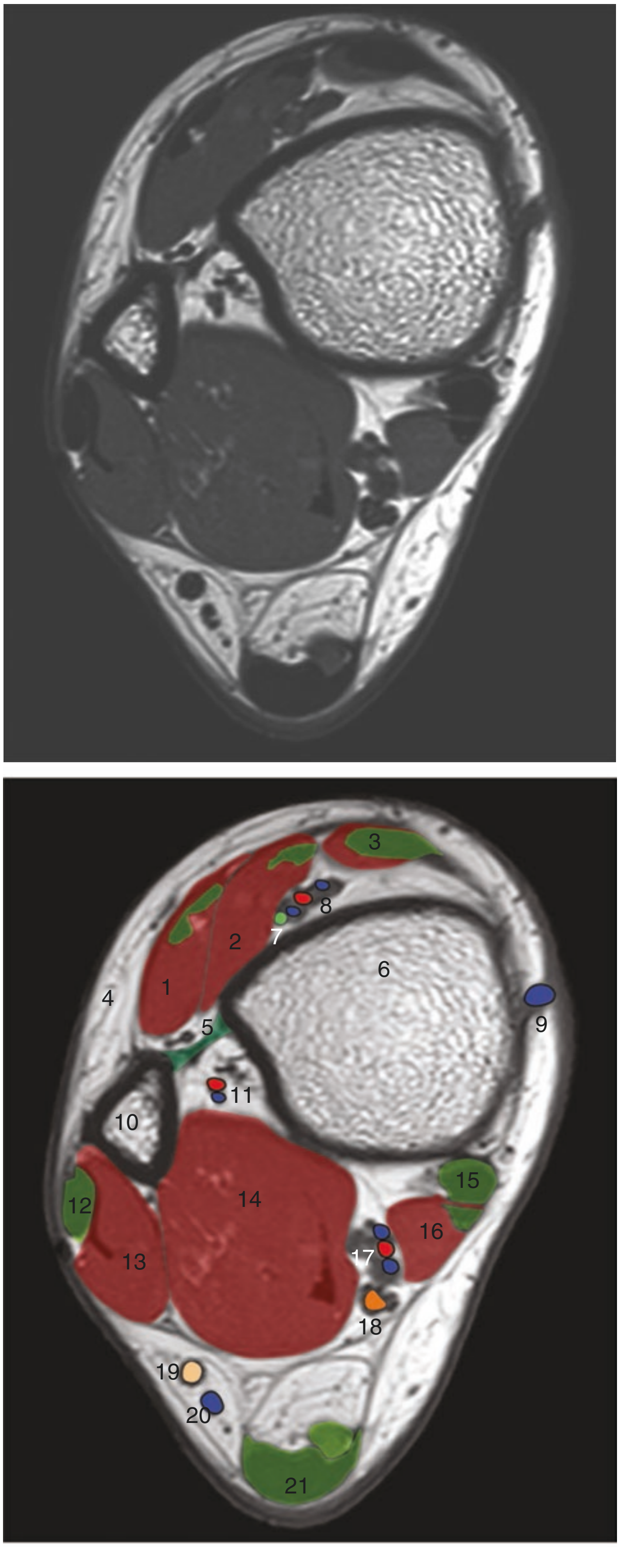


Figure Sc13. MRI scans at the distal third of the leg through the sciatic nerve and its terminal branches.





1- Extensor digitorum longus muscle

2- Extensor hallucis longus muscle

3- Tendon of the tibialis anterior muscle

4- Superficial fibular nerve

5- Interosseous membrane

6- Tibia

7- Deep fibular nerve

8- Anterior tibial artery and vein

9- Great saphenous vein

10- Fibula

11- Fibular artery and vein

12- Tendon of the peroneus longus muscle

13- Peroneus brevis muscle

14- Flexor hallucis longus muscle

15- Tendon of the posterior tibial muscle

16- Flexor digitorum longus muscle

17- Posterior tibial artery and vein

18- Tibial nerve

19- Sural nerve

20- Small saphenous vein

21- Tendons of the triceps surae and plantaris muscles

Figure Sc14. MRI scans in the ankle through the sciatic nerve and its terminal branches.

Pathology

The sciatic nerve is the terminal branch of the sacral plexus.

It goes out of the pelvis between the pyramidalis and superior gemellus muscles and then goes down on the posterior face of the thigh until the popliteal fossa, where it divides into its two terminal branches, the tibial and common fibular nerves (Figure Sc2).

In the thigh, it does not have its own sensitive function, but it innervates the muscles of the posterior compartment of the thigh (Figure Sc7). It takes charge of the flexion of the leg on the thigh, of the extension of the thigh on the torso and of the foot's mobility.

Aetiology

- Compression: Multiple events can cause compression of the sciatic nerves, amongst which pregnancy and injuries caused by tumours are noteworthy.
- Section: Truncal injuries of the sciatic nerve generally occur outside of the lesser pelvis. Iatrogenic complications can occur during an intramuscular injection in the buttock near the position of the nerve.
- Traction/stretching: Particularly in cases of posterior dislocation of the hip or related to the dislocation itself or as an iatrogenic complication during its reduction (Figure Sc15).

Femoral fractures where the two parts of the bone are out of alignment (displaced fracture) and rather far from each other can cause an injury of the sciatic trunk either because of direct stress or because of stretching (Figure Sc16).

Clinical Significance

The clinical signs can evoke an L5 or S1 leg pain.

- Sensitive signs: They concern a direct injury of the nerve.
- Hypoesthesia affects the territories of the terminal branches of the sciatic nerve, which are the lateral face of the leg, and the territory of the fibular nerve and the foot.
- The pain is often localized in the buttock or at the compression point. The fact that the pain worsens at night can suggest an ischial bursitis.
- Motor signs: These can concern the muscles of the leg that are innervated by the terminal branches of the sciatic nerve, or those directly innervated by it in the thigh. A deficit of all the muscles of the posterior compartment of the thigh, of the leg or even of the foot can then be noticed according to the injury's level of seriousness. The extension of the thigh on the torso, the flexion of the leg on the thigh and dorsiflexion of the foot can suffer from a deficit.

Clinical Forms

- Piriformis syndrome: The piriformis muscle can make contact with the posterior cutaneous nerve of the thigh and the sciatic nerve. The posterior cutaneous nerve of the thigh is the first to be affected, and the pain often only goes down to the popliteal fossa.
- Obturator internus syndrome: The compression occurs where the nerve goes between the obturator internus and piriformis muscles, a point where the pudendal nerve can also be affected. The pain can then invade the territory of the pudendal nerve in a concomitant manner.

Explorations

- An MRI of the speculated compression area can be very informative by searching for a very frequently found extrinsic cause, after clinical orientation.
- An electroneuromyography will objectify the electrophysiological injury of the nerve.

Treatment

If there is no expansive process, the first treatment would be medical, associating a treatment of the pain with physiotherapy and antalgic medication, and then eventually resorting to corticosteroid injections. Surgery is only rarely adopted.

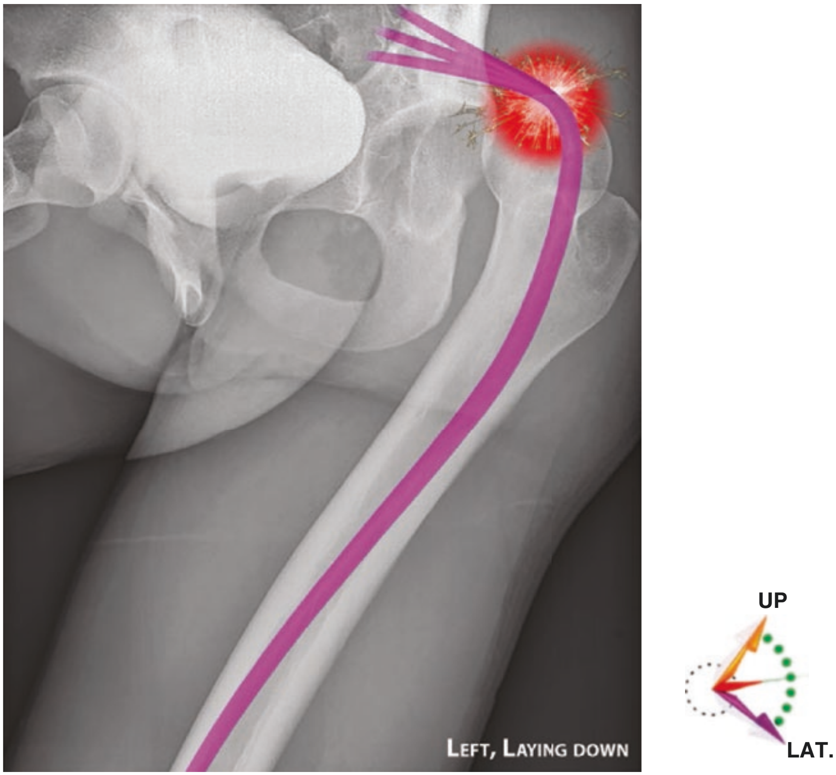

LEFT, LAYING DOWN
UP
LAT.

Figure Sc15. Traumatic posterior hip dislocation, which can be responsible of a sciatic nerve trunk injury.

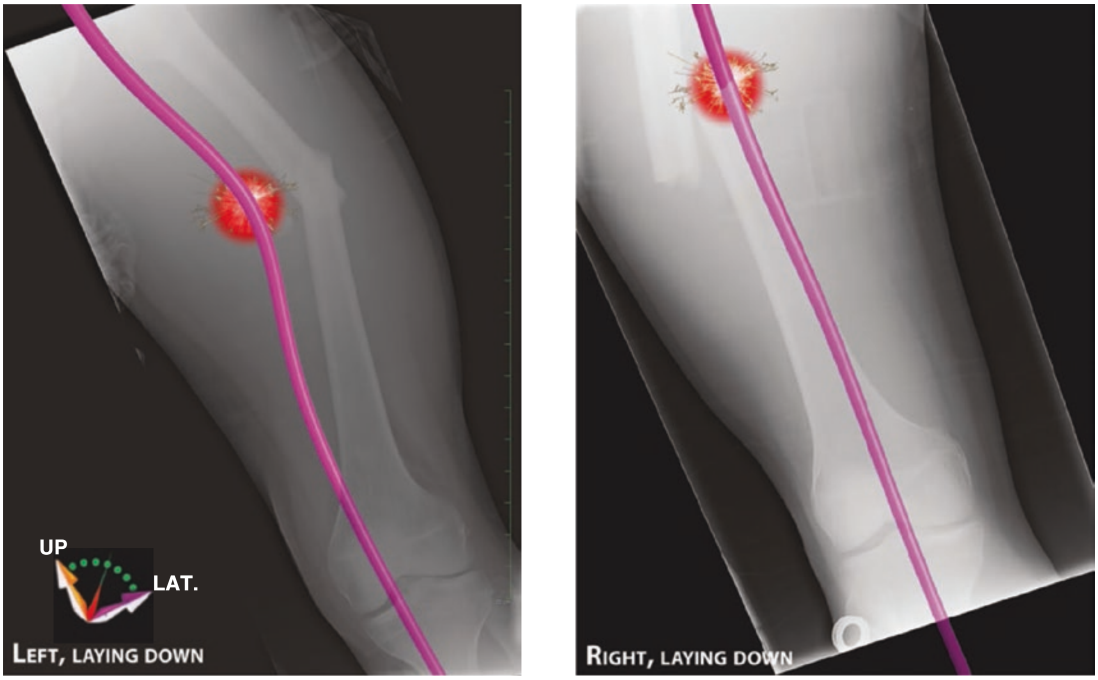

UP
LAT.
LEFT, LAYING DOWN
RIGHT, LAYING DOWN

Figure Sc16. Diaphyseal femur fracture with neurological signs.

Morphological Data: Sono Anatomy

Ultrasonographically, the sciatic nerve is the terminal branch of the sacral plexus. It exits the pelvis through the incision of the greater sciatic notch, below the pirifomis muscle to descend into the region of the buttock and then to the posterior thigh surface to the popliteal fossa, where it is divided into two terminal branches: the tibial nerve and the common fibular nerve.

At the greater sciatic notch level, it is lateral to the inferior gluteal artery and the pudendal vascular nerve bundle.

At the buttock, it descends into a gutter between the ischium and the greater trochanter at the posterior and deep surface of the gluteus maximus muscle. More deeply, on its anterior surface, there is the muscular plane of the obturator internus, quadratus femoris and gemellus muscles.

In the thigh, the sciatic nerve is accompanied by its artery. It is covered by the long leader of the biceps femoris muscle. The nerve is placed between the fascia of the semimembranosus muscle and the long head of the biceps femoris muscle.

When these muscles diverge, at the roof of the popliteal fossa, the nerve is divided into its terminal branches. The ultrasound procedure below corresponds to the technique used to infiltrate the periphery of the nerve, in a piriformis syndrome.

Installation

The patient is positioned in a ventral position. The markers are the top of the buttock, the iliac bone and the gluteus maximus muscle, corresponding respectively to the skin, bone and muscle markers.

Equipment and Location

- Probe type: linear, high frequency
- Probe axis: axial
- Parameter setting: 5 cm deep

Ultrasound Procedure

The probe is positioned in the axial plane. The first marker to be identified corresponds to the posterior superior iliac spine, and a slight lateral and caudal curve is then made, to align virtually on the axis of the piriformis muscle, going from the sacrum to the greater trochanter, "walking" to the surface and along the gluteus maximus muscle. The probe must then be lowered until the large ischiatic hole is visible. All vascular nerve structures, including the sciatic nerve innervating the pelvis and buttock, pass through the large ischial hole. The piriformis muscle, on the other hand, is the only muscle that passes through the large ischiatic hole.

The piriformis muscle appears in a characteristic "pear" shape at the depth of the gluteus maximus muscle.

It is important at this stage to identify the sciatic nerve to assess its depth and subsequently avoid inadvertently puncturing it or having the anaesthetic agent diffuse to its level. As soon as identification of the sciatic nerve has been performed, a slight translation in the cranial direction is performed to locate the muscle body of the piriformis muscle. It is necessary to verify that it is indeed the piriformis muscle, by alternating internal/external rotation movements of the bent knee, to mobilize the muscular body. These movements must be performed by a third party and not by the patient himself. This will help to differentiate the gluteus maximus muscle from the piriformis muscle in overweight patients. A very large number of anatomical variations of the sciatic nerve have been described, with fairly frequent intramuscular crossings:

In 74–84% of cases, it passes under the piriformis muscle but in 12–21% of cases, there is an aberrant path of the nerve through the muscle.

Piriformis Syndrome

Piriformis syndrome can mimic disc sciatica. It is a differential diagnosis. Pain is most often truncated, extremely positional and pseudo-radicular. Lasègue is negative. Manoeuvres to tighten the muscle, by internal rotation of the hip, trigger irradiation, with the patient in decubitus, knee and hip bent. It must then be discussed and eliminated by ultrasound as a positive diagnostic tool. In case of doubt, MRI of the lumbosacral spine and EMG will explore the spine. Morphological MRI of the small pelvis will eliminate compression of tumour aetiology and search potential muscle conflict, asymmetry, inflammatory hypersignal, vascular loops and nerve oedema. The range of treatments will exclude possibilities of drug analgesics, physiotherapeutic mobilizations to relax the muscle, infiltrations or the use of botulinum toxin (botulinum toxin) directly intramuscularly. Only in cases of refractory syndrome and highly suspected conflict, surgical exploration can be discussed.

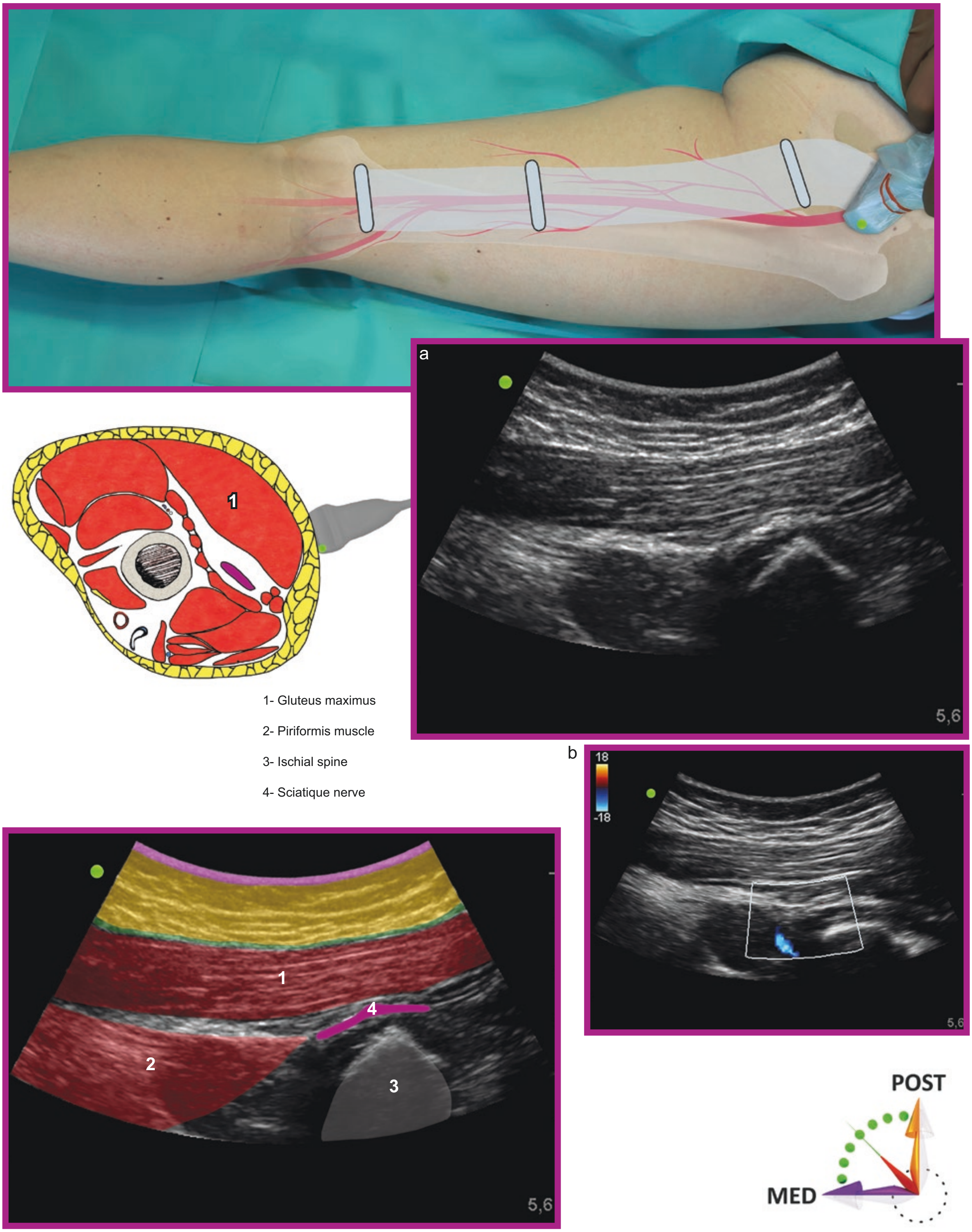
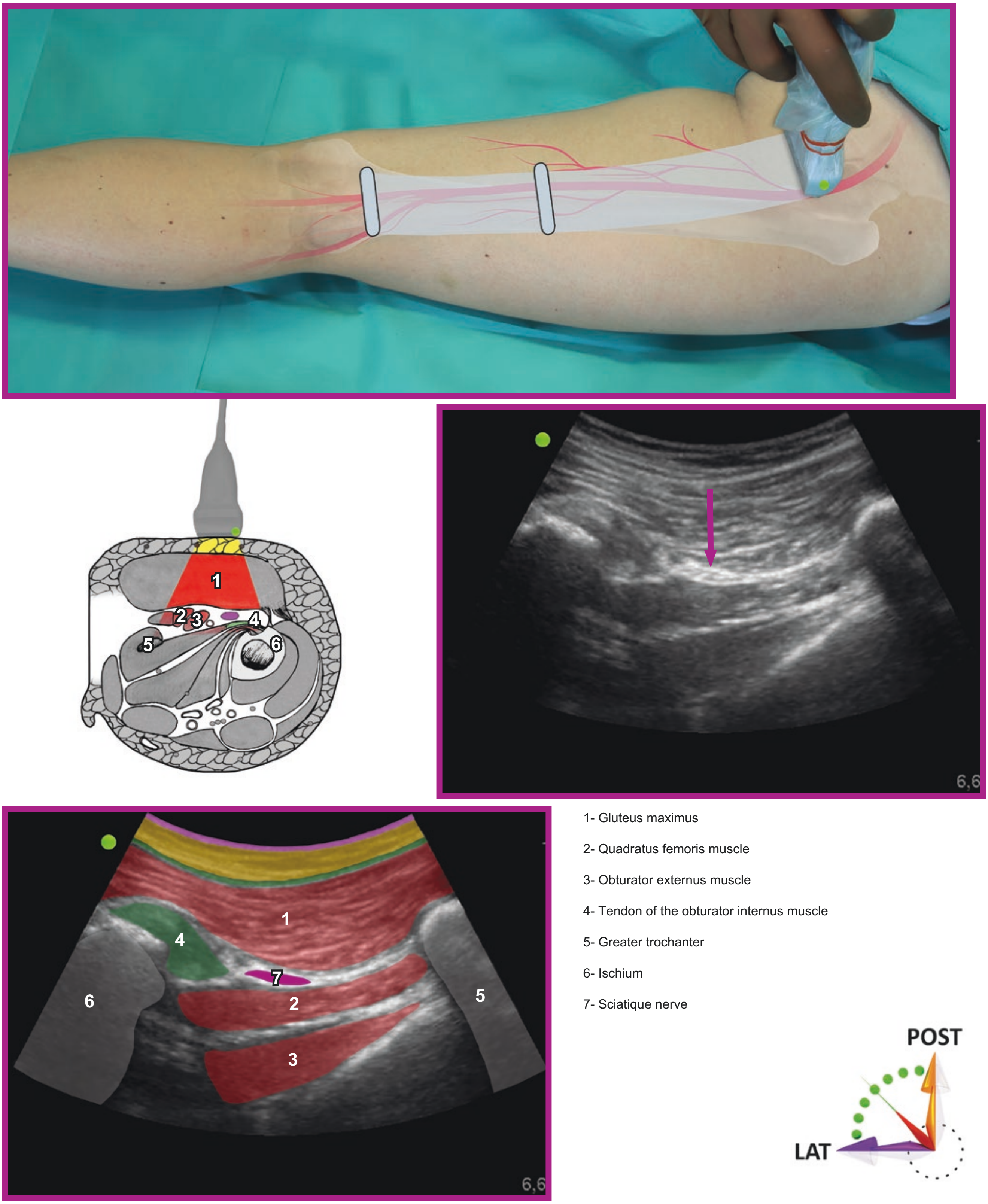

a
1
5,6
1- Gluteus maximus
2- Piriformis muscle
3- Ischial spine
4- Sciatique nerve
b
18
-18
5,6
1
4
2
3
5,6
POST
MED

Figure Sc17. (**a**) Ultrasound transversal views of the sciatic nerve at the infra-piriform foramen. (**b**) Doppler mode view.



1- Gluteus maximus

2- Quadratus femoris muscle

3- Obturator externus muscle

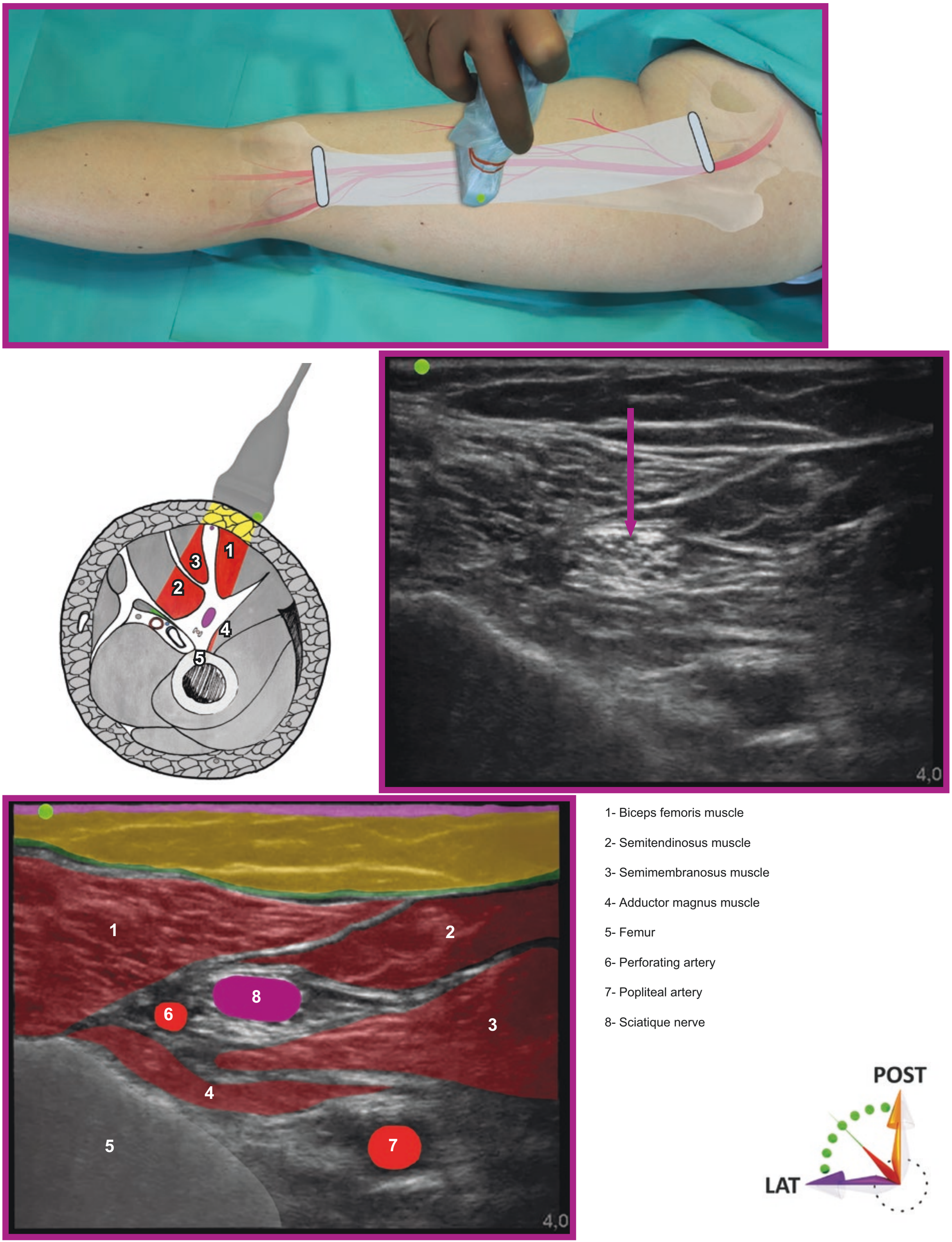
4- Tendon of the obturator internus muscle

5- Greater trochanter

6- Ischium

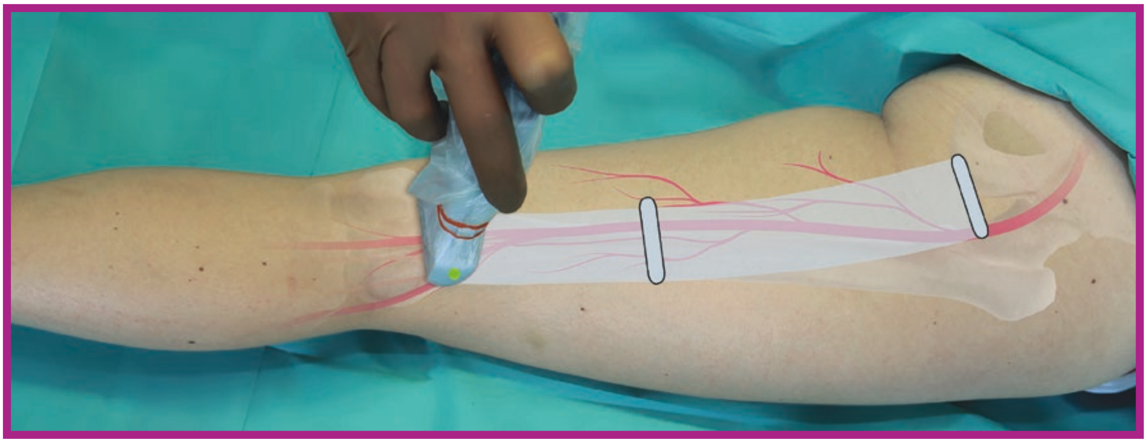
7- Sciatique nerve

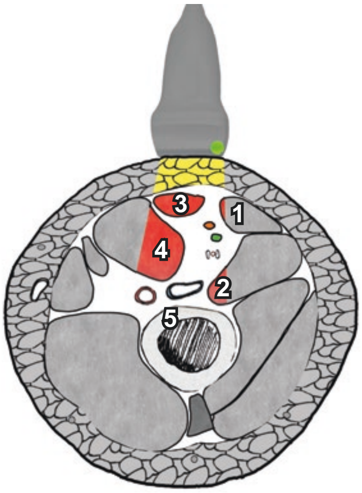
Figure Sc18. Ultrasound transversal views of the sciatic nerve at the sub-gluteal region.

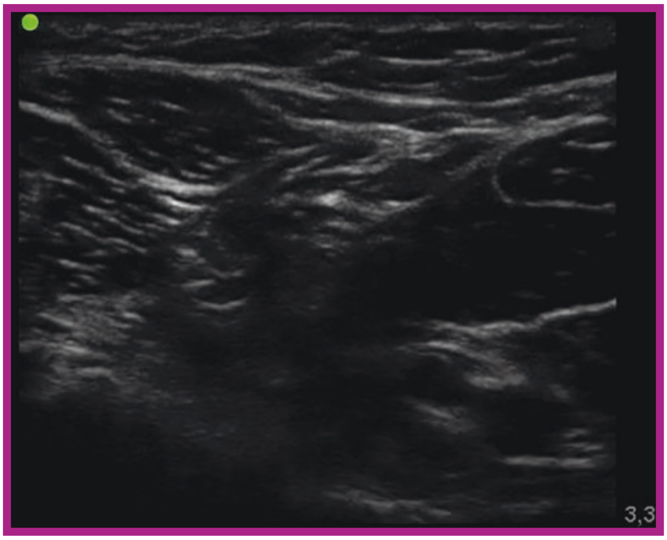


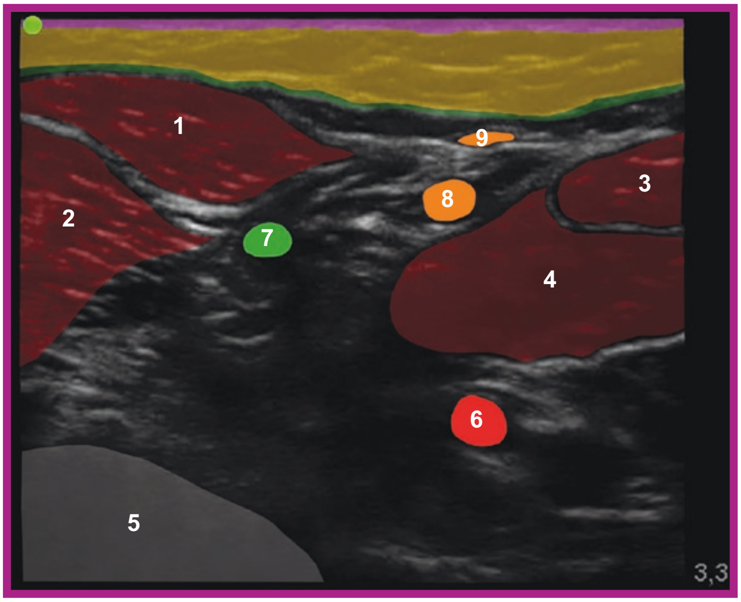
1- Biceps femoris muscle
2- Semitendinosus muscle
3- Semimembranosus muscle
4- Adductor magnus muscle
5- Femur
6- Perforating artery
7- Popliteal artery
8- Sciatique nerve

Figure Sc19. Ultrasound transversal views of the sciatic nerve at the middle tier of the tight, before its division into terminal branches.









1- Long head of the biceps femoris muscle
2- Short head of the biceps femoris muscle
3- Semitendinosus muscle
4- Semimembranosus muscle
5- Femur
6- Popliteal artery
7- Fibular nerve
8- Tibial nerve
9- Medial sural nerve

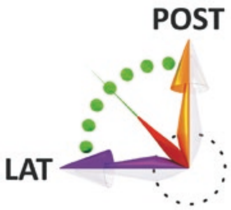


Figure Sc20. Ultrasound transversal views of the sciatic nerve division at the popliteal fossa level.

Interventional Procedure

Infiltration/Test Block

Indication

Ultrasound is an attractive technique for infiltrating the piriformis muscle, as mentioned above.

This technique allows visualization of the needle throughout the procedure—if an "in plane" ultrasound approach is chosen—as well as the adjacent neurovascular structures.

It allows injection of corticosteroids or botulinum toxin into the muscle.

Technique

- After locating the piriformis muscle, the infiltration needle is placed "in plane".
- It is a muscle block with intramuscular injection of anaesthetic or botulinum toxin.
- Progression of the needle is from lateral to medial.
- Considering intramuscular injection and aberrant sciatic nerve paths, use of neurostimulation makes it possible to differentiate between the gluteus maximus and piriformis muscles and to avoid nerve trauma associated with an aberrant intramuscular path.
- It is possible to make injections in the upper fascia, between the gluteus maximus and piriformis muscles, to avoid diffusion more in depth of the product on the sciatic nerve.

PNS

Technique

- The patient is in prone position.
- We recommend an implantation site downstream of the lesion that causes neuropathic symptomatology, especially when the nerve is sandwiched in the aponeurosis, resulting from the combination of the fascias of the long head of the biceps femoris and the semimembranosus muscle.
- Type of ultrasound probe: linear, high frequency.
- The ultrasound probe is positioned perpendicular to the nerve, which will be positioned in the middle of the screen.
- This will make it possible to anticipate projection of the nerve over a few centimetres, so as to prepare the lead placement, which will be carried out according to the "out of plane" technique.
- The direction of the needle and the stimulation lead will be oriented towards distality.
- A hydrodissection and, if possible, an intraoperative stimulation test should be performed if the patient is under light anesthesia or intravenous anesthesia with the objective of concentration.
- It is ideal to visualize at least two plots in contact with the nerve to confirm the proximity of the lead and optimize the coverage, analgesic effect and energy consumption of the device.

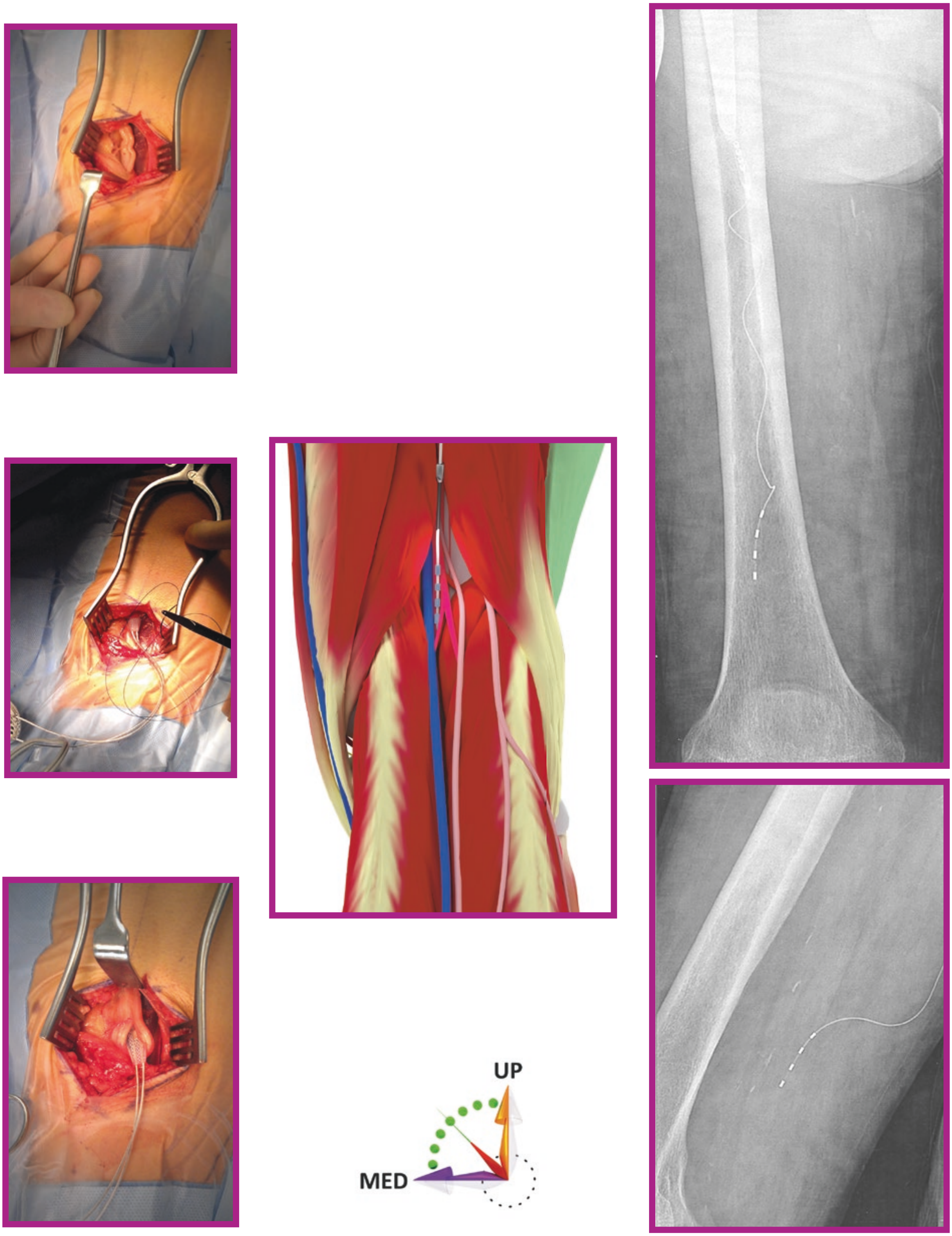


Figure Sc23. An illustrative view of sciatic nerve neurostimulation at the tight level.

Surgical Procedure

Surgical Indications

- Nerve repair after direct nerve trauma.
- Removal of a sciatic nerve schwannoma, responsible for atypical sciatica.

Surgical Approaches

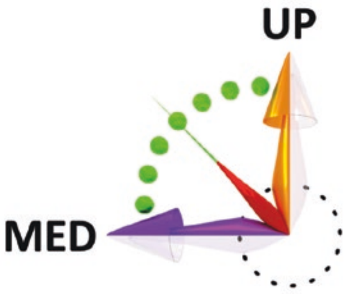
On the Buttock

Skin Incision

For the approach from the nerve to the buttock, the incision starts from the posterior superior iliac spine to curve quickly and surround the lateral edge of the gluteus maximus muscle. It passes behind the greater trochanter and joins the gluteal fold. It curves to become vertical, to widen if desired the approach downwards and the thigh. At the thigh, the incision will be vertical from the gluteal fold to the lateral edge of the popliteal fossa and the projection of the fibular nerve path.

Nervous Exposure

At the buttock, the fascia and gluteus maximus muscle are incised and then reflexed inward to expose the pelvic-trochanteric muscles. The nerve is then found as described in the section "Morphological Data". It is pressed against the hip stabilizing muscles, "walking" outside the posterior cutaneous nerve of thigh nerve. To follow it upwards, the tendon of the piriformis muscle can be severed and reflexed inwards to access the point of emergence of the nerve at its exit from the pelvis (Figure Sc24).



1- Sciatique nerve
2- Inferior gluteal nerve
3- Superior gluteal nerve
4- Posterior cutaneous nerve of the thigh
5- Gluteus minimus
6- Gluteus maximus
7- Piriformis muscle
8- Biceps femoris muscle
9- Semimembranosus muscle
10- Semitendinosus muscle
11- Greater trochanter
12- Intertrochanteric crest

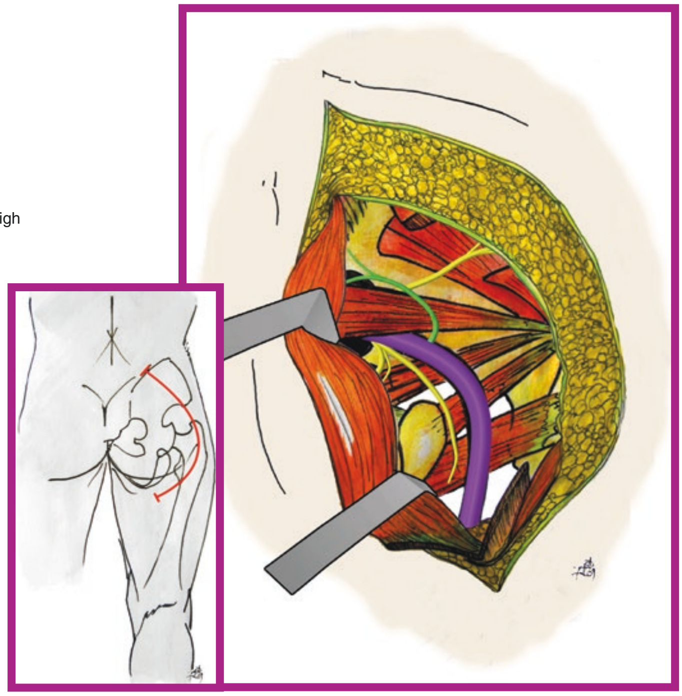


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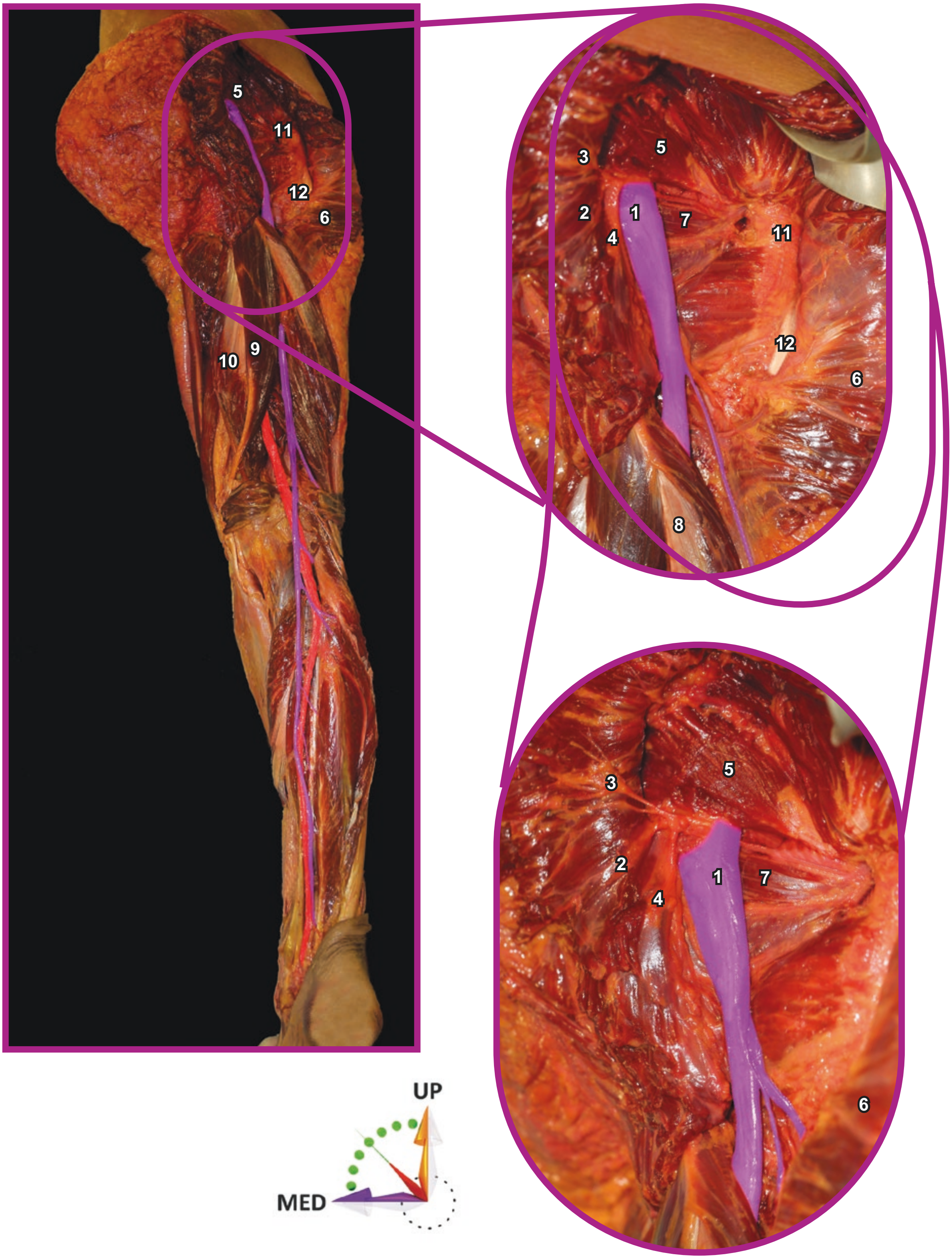
Figure Sc24. Surgical approach of the sciatic nerve at the gluteal region.


5
11
12
6
10
9
3
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2
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4
11
12
6
8
5
3
2
1
7
4
6
UP
MED

Figure Sc25. Surgical approach of the sciatic nerve at the gluteal region.

At the Thigh

Skin Incision

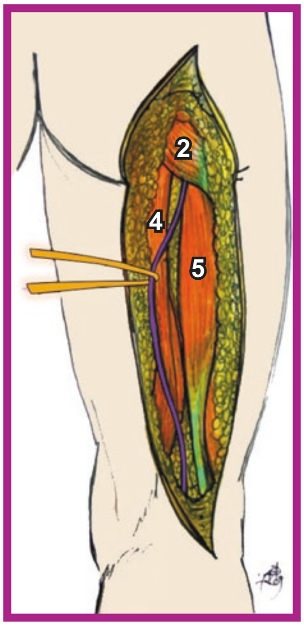
The aponeurosis is carefully incised inside the posterior cutaneous nerve of thigh nerve, which travels over the surface of the biceps femoris muscle (Figure Sc26).

Nervous Exposure

The semitendinosus muscle is recoiled on one side and the biceps femoris muscle on the other side to find the sciatic nerve, in a bed of fat housing many branches of muscle vascularization and multiple perforators often retro-crossing the nerve. It can be followed to its junction at the top of the popliteal fossa, where it is divided into tibial and fibular nerves, each disengaging the lateral sural cutaneous nerve outside and the medial sural cutaneous nerve inside quite quickly on their inner side.

Technical Pitfalls

- Damage to exposed nerves and neighbourhood vessels, especially in the event of prolonged use of spatulas, valves, etc.
- Insufficient re-stocking of the gluteus maximus and its fascia.
- Bleeding from the perinervous venous plexus responsible for a post-operative posterior thigh hematoma.



1- Sciatique nerve
2- Gluteus maximus
3- Semimembranosus muscle
4- Semitendinosus muscle
5- Biceps femoris muscle
6- Femoral artery

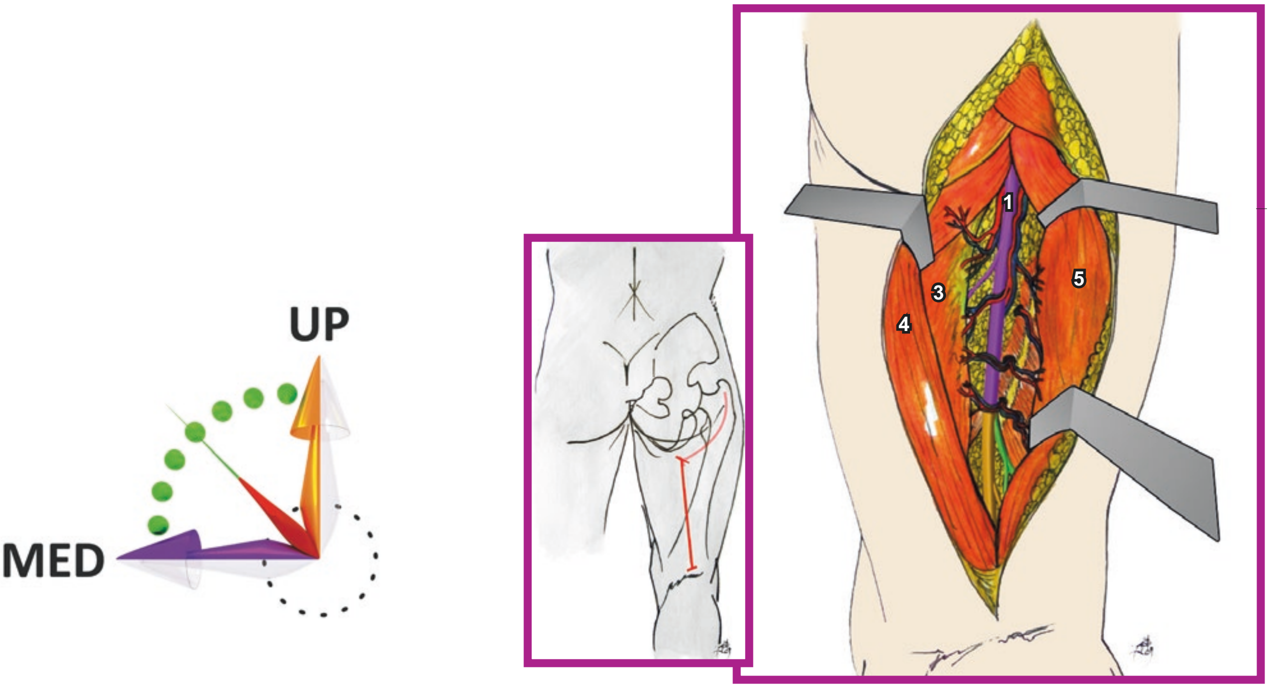
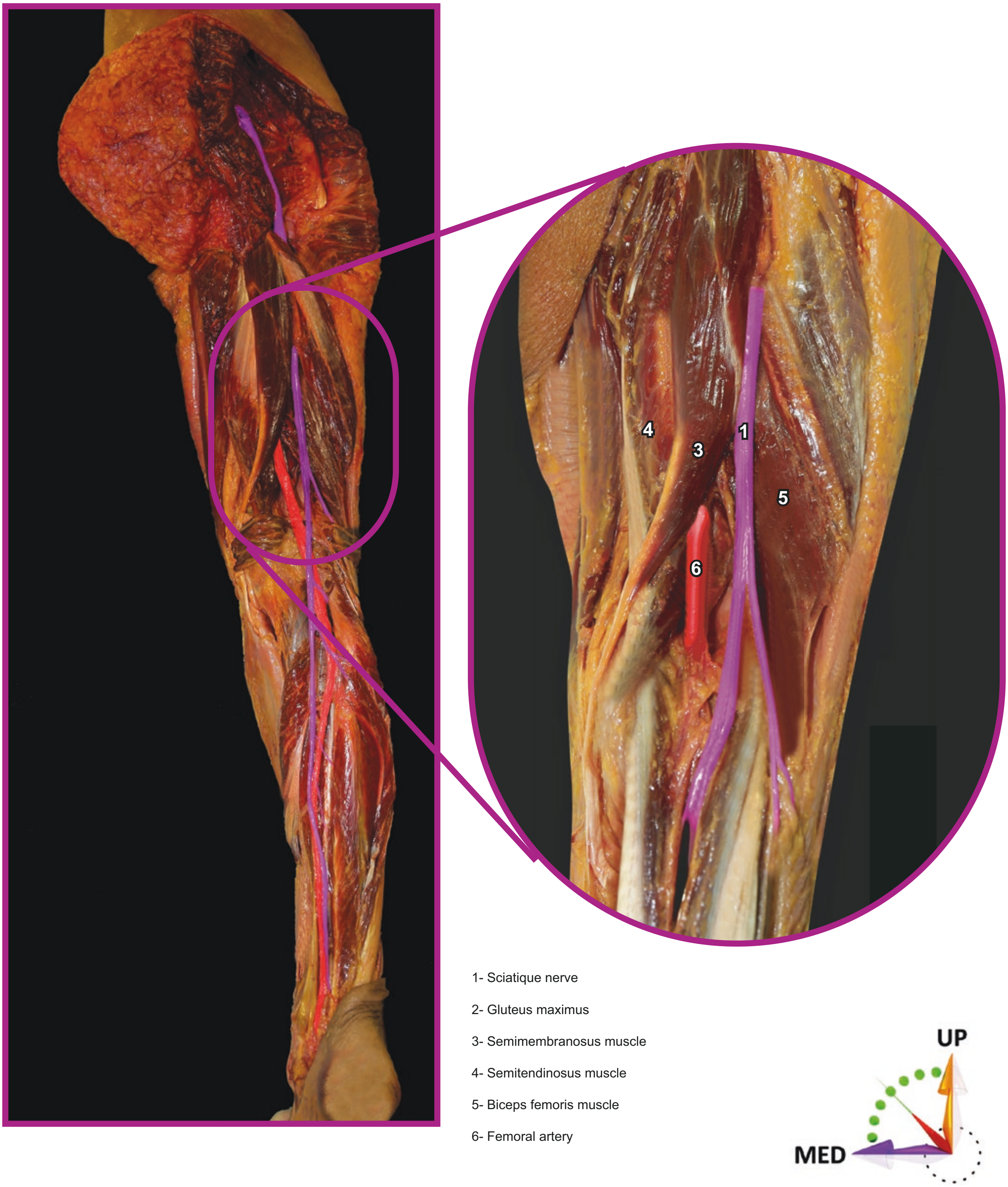


Figure Sc26. Surgical approach of the sciatic nerve at the tight level.



1- Sciatique nerve
2- Gluteus maximus
3- Semimembranosus muscle
4- Semitendinosus muscle
5- Biceps femoris muscle
6- Femoral artery

Figure Sc27. Surgical approach of the sciatic nerve at the tight level.

T11
T12
L1
L2
L3
L4
L5

The Obturator Nerve

The Femoral Nerve

The Sciatic Nerve

The Tibial Nerve

The Common Fibular Nerve

The Lateral Femoral cutaneous Nerve

Others Nerves

The Tibial Nerve

Morphological Data

The tibial nerve is a mixed nerve and the main and medial terminal branch of the sciatic nerve. It innervates the muscles of the posterior compartment of the leg and the plantar face of the foot whilst going behind the medial malleolus.

Origin

The tibial nerve is the most voluminous terminal branch of the sciatic nerve. It is constituted of the same roots as this nerve: L4, L5, S1, S2 and S3 (Figures. T1 and T2). It begins at the upper angle of the popliteal fossa. At this level, it faces the fibular nerve laterally, which is the lateral terminal branch of the sciatic nerve (Figure T2).

Path

In the popliteal fossa, it goes down vertically, medially related to the popliteal vein then to the popliteal artery (Figures T3, T4 and T5). This neurovascular pedicle is enclosed by a muscular embedment (Figure T3). This coat has the shape of a diamond, delimitated by:

- Above and medially: the semitendinosus and semimembranosus muscles
- Above and laterally: the biceps femoris muscle
- Below and medially: the medial head of the gastrocnemius muscle
- Below and laterally: the lateral head of the gastrocnemius muscle

It then penetrates into the posterior compartment of the leg, going in front of the tendinous arch of the soleus muscle and then lying against the interosseous membrane, thus forming the posterior tibial neurovascular bundle (Figure T5). It faces the soleus muscle in behind and, above this area, the crural fascia below and faces in succession the tibialis posterior and the flexor digitorum longus muscles in front.

In the ankle, the tibial nerve is situated inside the calcaneal tendon and then under the posterior tibial artery, behind the medial malleolus (Figure T6). At this level, the neurovascular pedicle is surrounded by the tendon of the flexor digitorum longus muscle in front and by the tendon of the flexor hallucis longus muscle behind. These two tendons and the posterior tibial pedicle are maintained in the ankle by the flexor retinaculum, the insertion of which is on the medial malleolus of the tibia above and on the medial face of the calcaneus below (Figures T7 and T8).

In the inferior part of this path, the tibial nerve separates into two terminal branches: the medial and lateral plantar nerves (Figures T10, T11, T12 and T13).

Neurovascular Relations

In the popliteal fossa, the tibial nerve faces the popliteal artery medially, albeit a little more superficial because this artery lies against the posterior side of the tibial plateau and faces it through the intermediary of the popliteus muscle (Figure T5).

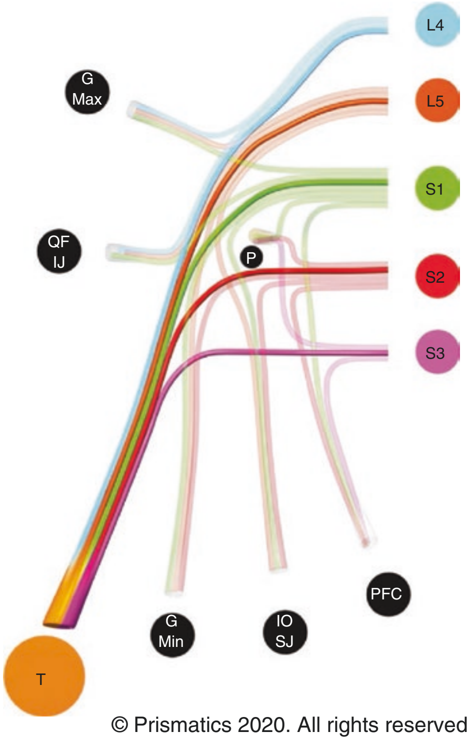


Figure T1. Origin of the tibial nerve, branch of the sciatic nerve.

Electronic Supplementary Material The online version of this chapter (https://doi.org/10.1007/978-3-030-49179-6_16) contains supplementary material, which is available to authorized users.

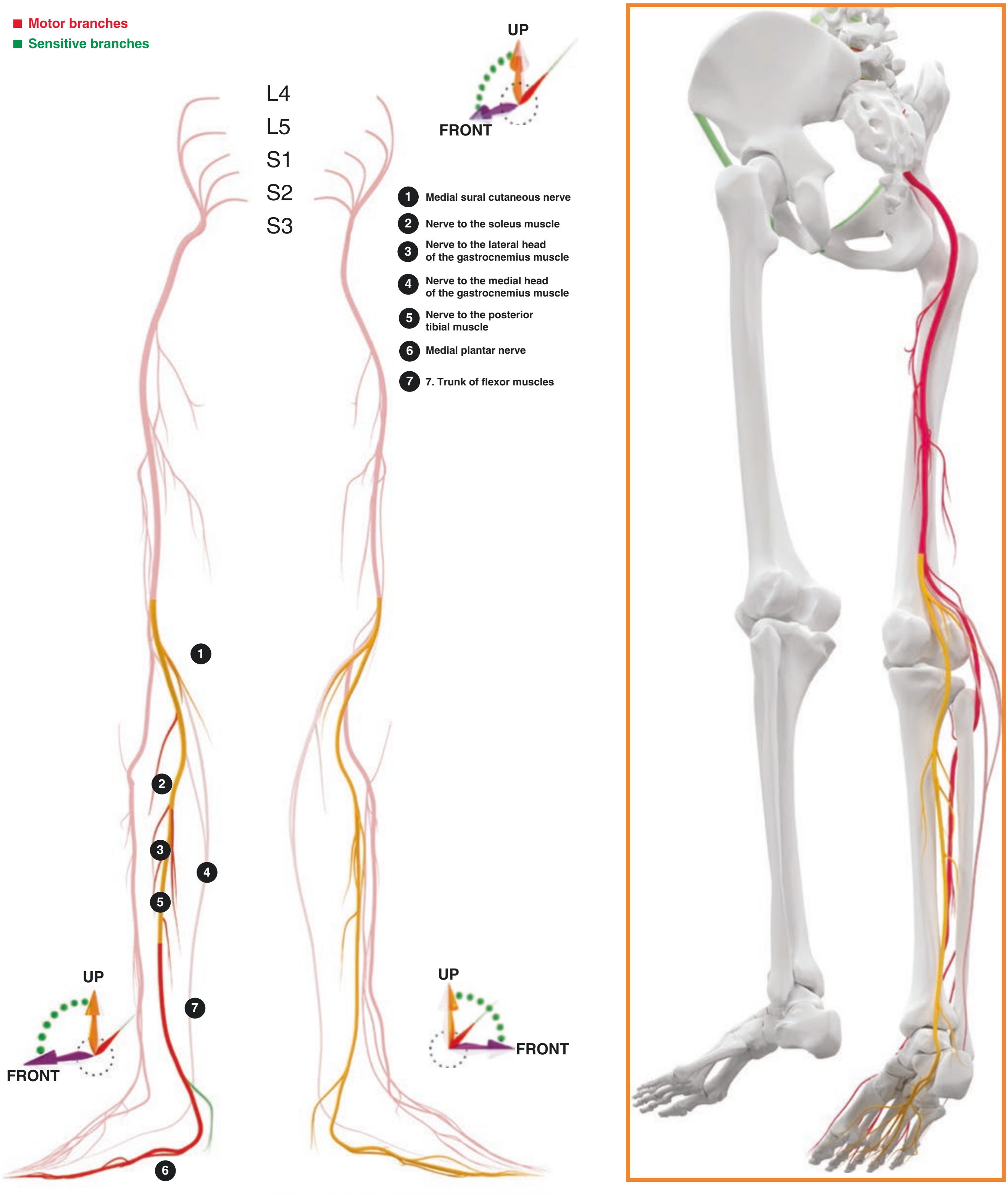
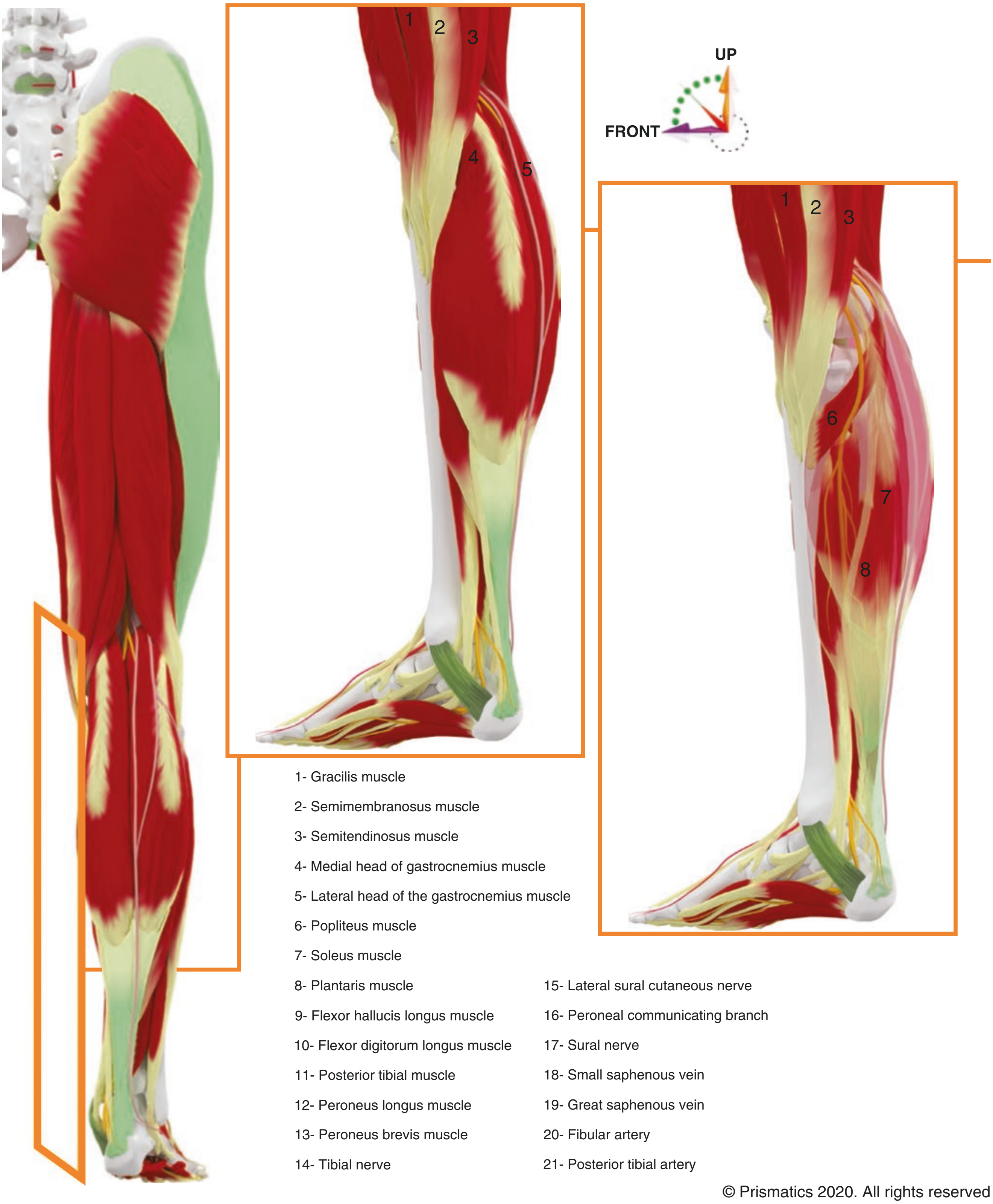

🟥 Motor branches
🟩 Sensitive branches
L4
L5
S1
S2
S3
UP
FRONT
1 Medial sural cutaneous nerve
2 Nerve to the soleus muscle
3 Nerve to the lateral head of the gastrocnemius muscle
4 Nerve to the medial head of the gastrocnemius muscle
5 Nerve to the posterior tibial muscle
6 Medial plantar nerve
7 7. Trunk of flexor muscles
1
2
3
4
5
7
6
UP
FRONT
UP
FRONT

Figure T2. Topographical distribution of the tibial nerve and its relations with bones.



1- Gracilis muscle
2- Semimembranosus muscle
3- Semitendinosus muscle
4- Medial head of gastrocnemius muscle
5- Lateral head of the gastrocnemius muscle
6- Popliteus muscle
7- Soleus muscle
8- Plantaris muscle
9- Flexor hallucis longus muscle
10- Flexor digitorum longus muscle
11- Posterior tibial muscle
12- Peroneus longus muscle
13- Peroneus brevis muscle
14- Tibial nerve
15- Lateral sural cutaneous nerve
16- Peroneal communicating branch
17- Sural nerve
18- Small saphenous vein
19- Great saphenous vein
20- Fibular artery
21- Posterior tibial artery

Figure T3. Muscular relations of the tibial nerve in the calf and ankle (from superficial to deep).

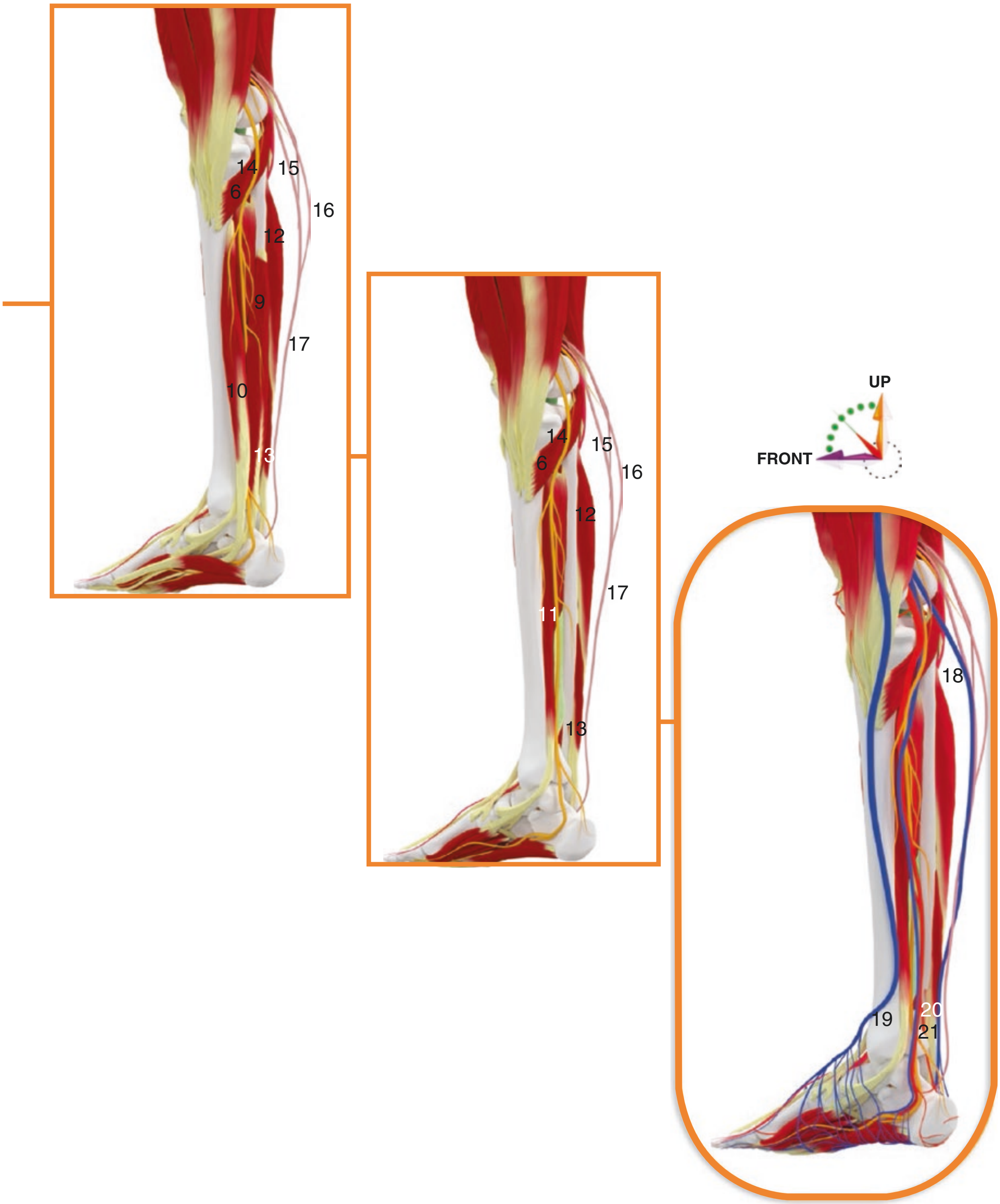

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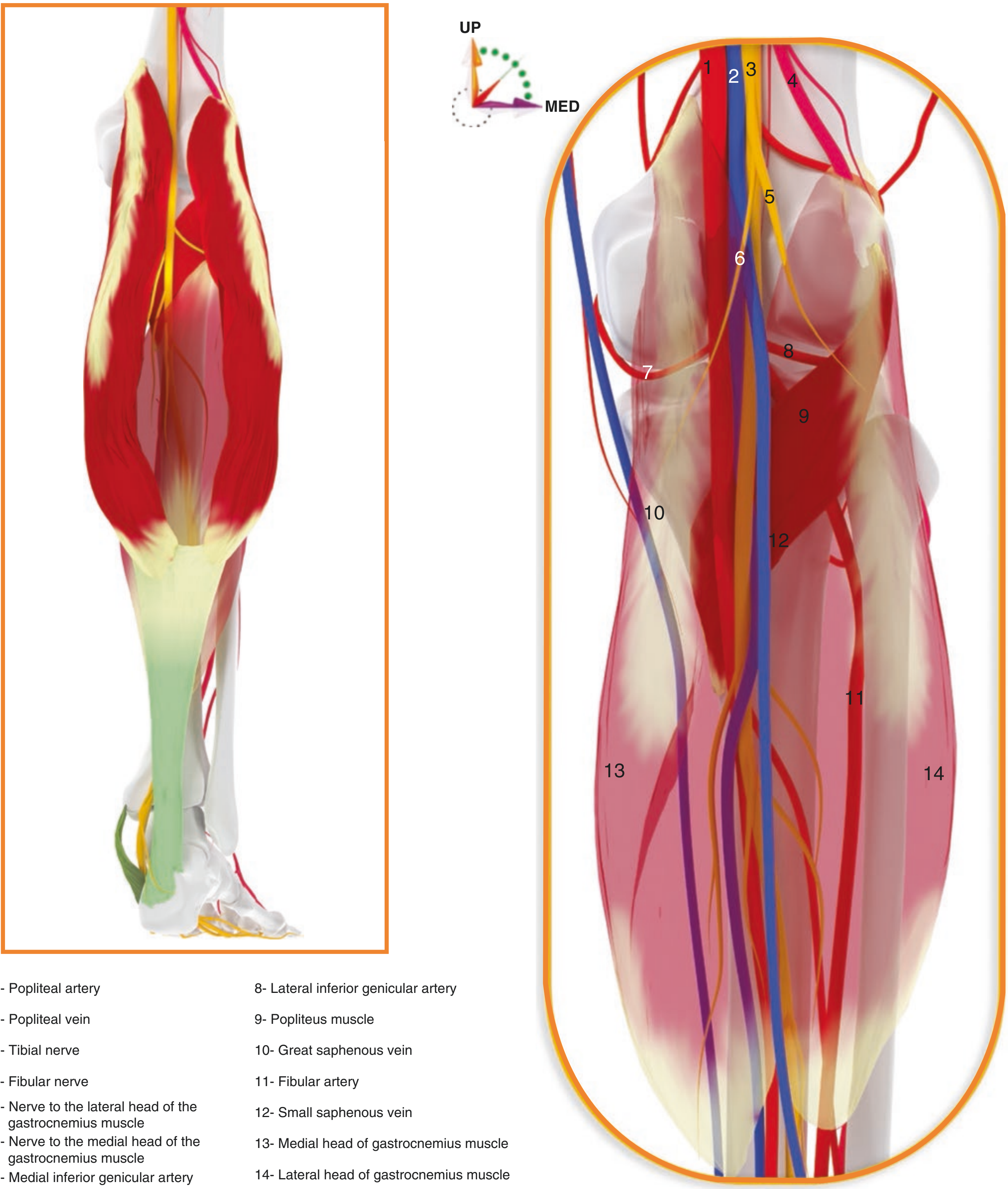
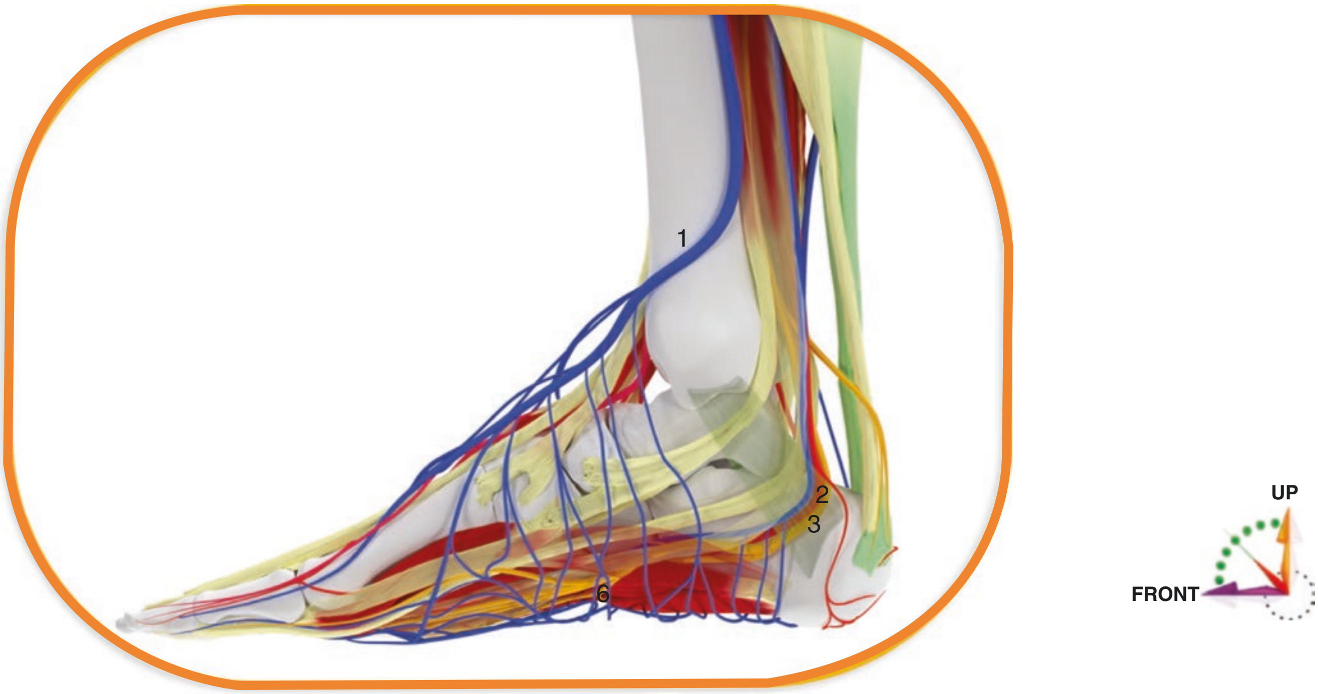
Figure T4. Neurovascular and muscular relations of the tibial nerve in the calf and ankle (from superficial to deep).



1- Popliteal artery
2- Popliteal vein
3- Tibial nerve
4- Fibular nerve
5- Nerve to the lateral head of the gastrocnemius muscle
6- Nerve to the medial head of the gastrocnemius muscle
7- Medial inferior genicular artery
8- Lateral inferior genicular artery
9- Popliteus muscle
10- Great saphenous vein
11- Fibular artery
12- Small saphenous vein
13- Medial head of gastrocnemius muscle
14- Lateral head of gastrocnemius muscle

Figure T5. Neurovascular relations of the tibial nerve in the popliteal fossa.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1- Great saphenous vein

2- Posterior tibial artery

3- Tibial nerve

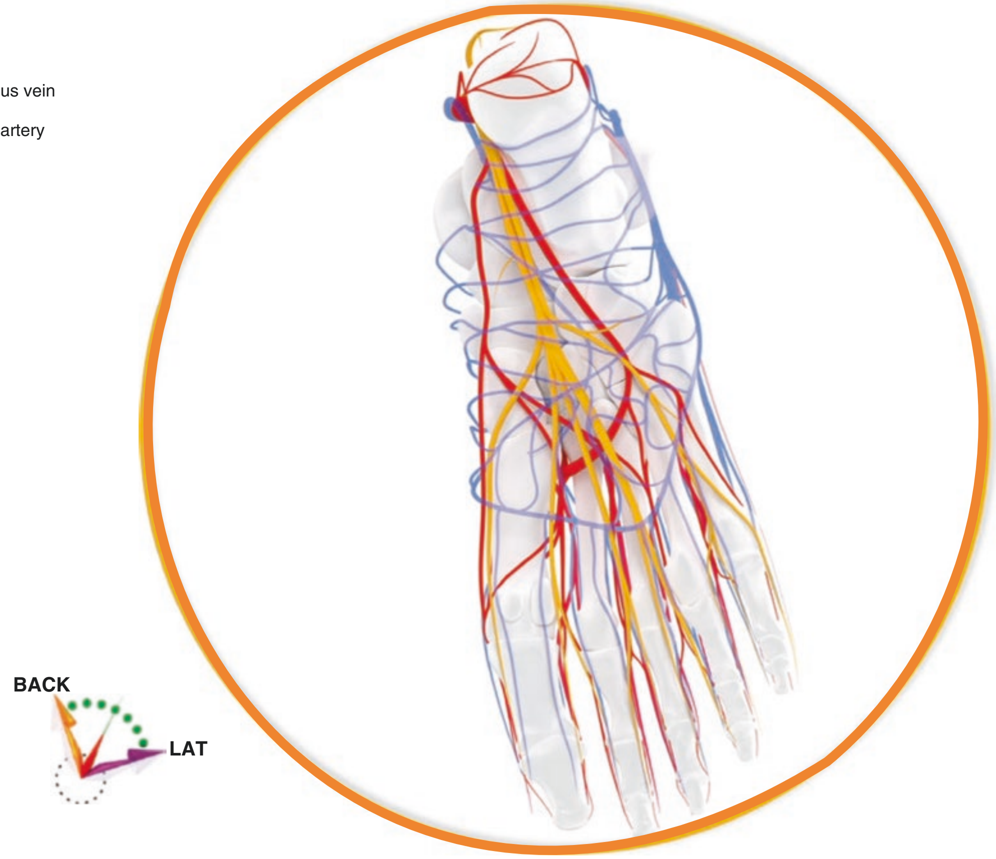
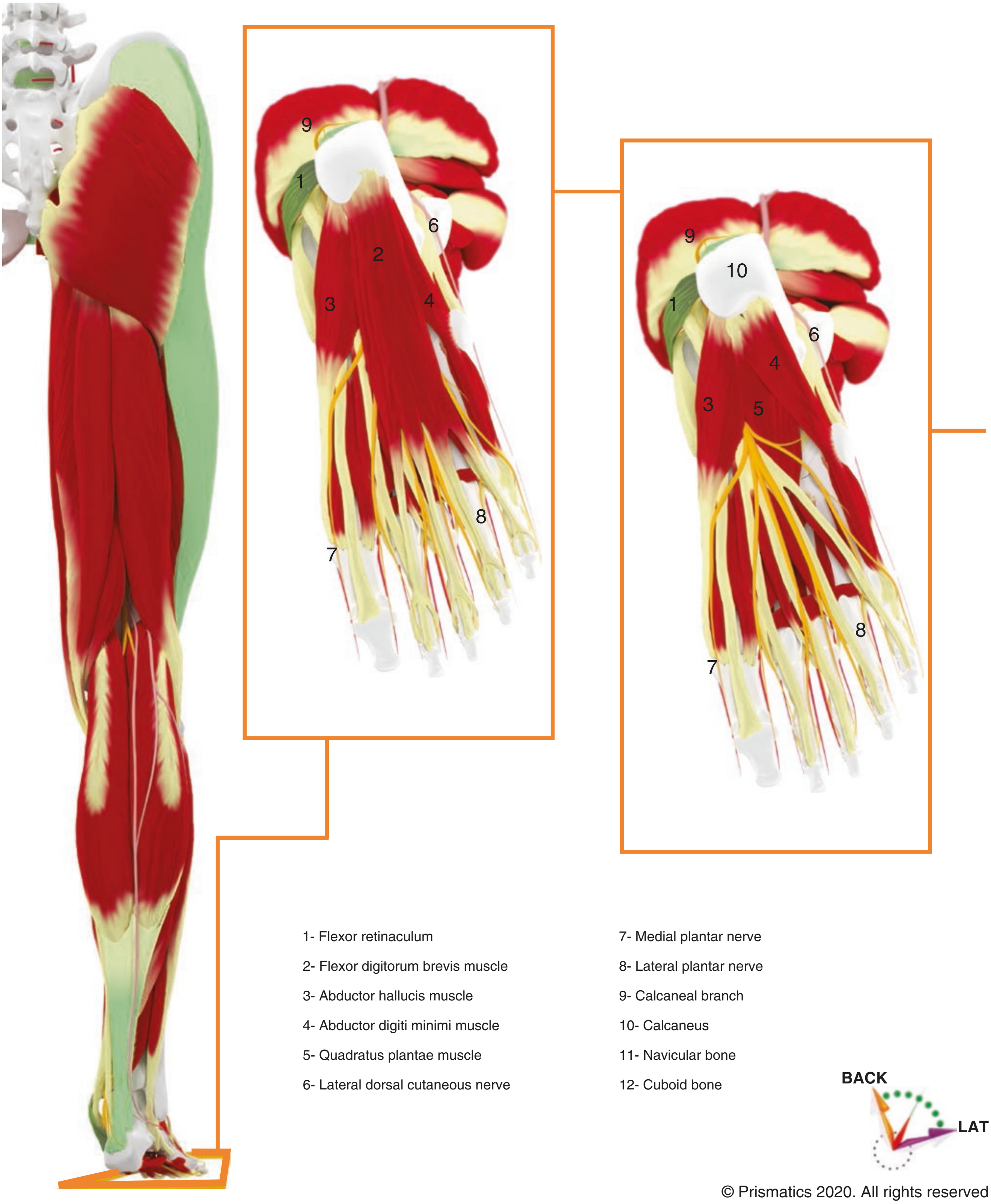


Figure T6. Neurovascular relations of the tibial nerve in the foot (median and inferior views).



1- Flexor retinaculum
2- Flexor digitorum brevis muscle
3- Abductor hallucis muscle
4- Abductor digiti minimi muscle
5- Quadratus plantae muscle
6- Lateral dorsal cutaneous nerve

7- Medial plantar nerve
8- Lateral plantar nerve
9- Calcaneal branch
10- Calcaneus
11- Navicular bone
12- Cuboid bone

Figure T7. Muscular relations of the tibial nerve in the foot (inferior view, from superficial to deep).

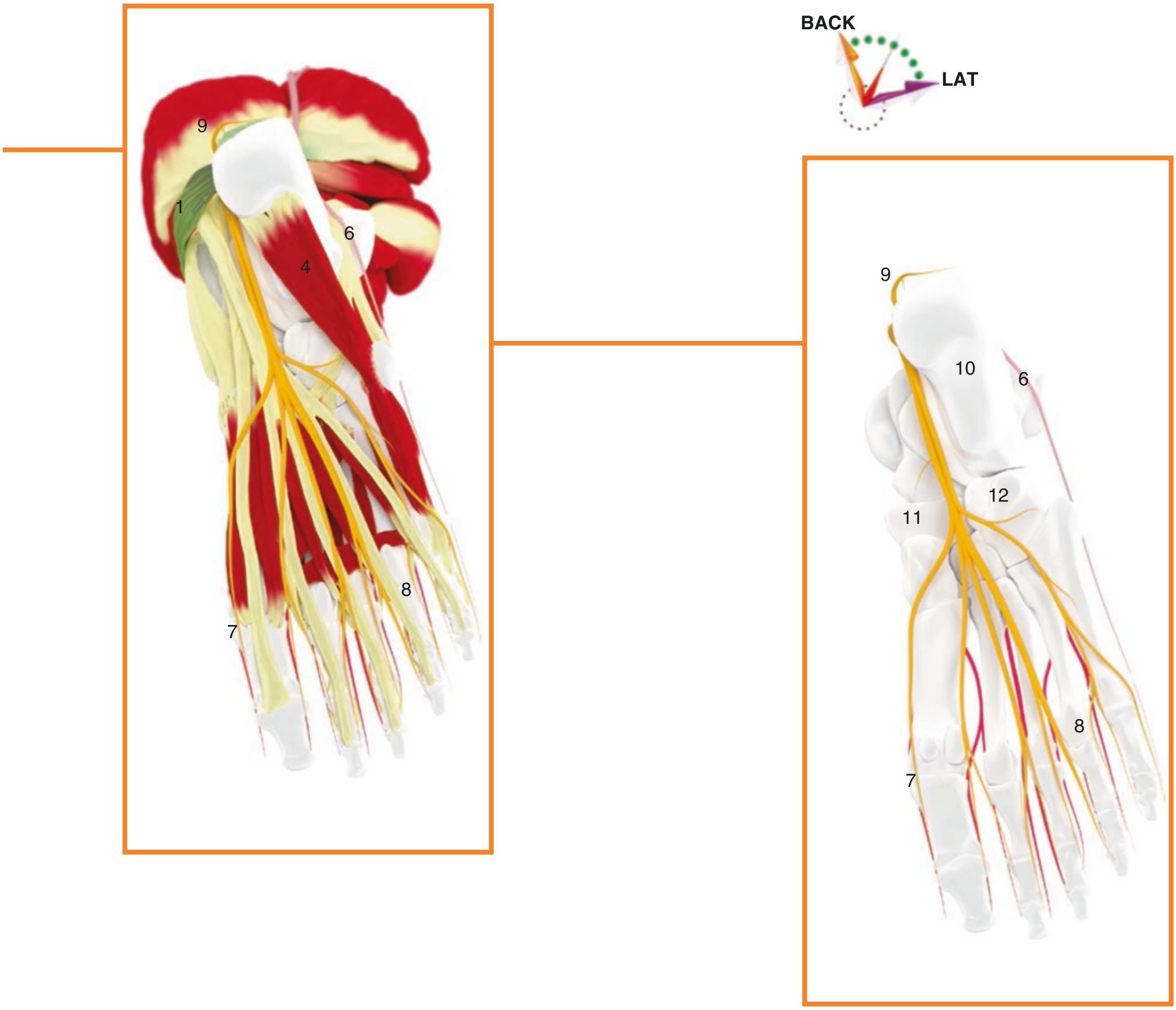

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Figure T8. Muscular relations of the tibial nerve in the foot (inferior view, from superficial to deep).

The Tibial Nerve

In the leg, the tibial nerve is situated behind and laterally related to the posterior tibial artery and its veins. Under the medial malleolus, the tibial nerve faces the posterior tibial artery above (Figure T6).

Collateral Branches

The tibial nerve gives off several types of collateral branches (Figure T2):

- Muscular branches for the muscles that it innervates: the soleus muscle, the plantaris muscle, the medial and lateral heads of the gastrocnemius muscles, the popliteus muscle, the tibialis posterior muscle, the flexor digitorum longus and the flexor hallucis longus muscles (Figure T4).
- Articular branches for the posterior face of the knee and the medial face of the tibiotarsal joint.
- Sensitive branches for the innervation of the teguments (Figures T4 and T9).

Amongst the sensitive branches, one noteworthy branch is the medial sural cutaneous nerve. This branch can merge with a lateral or a fibular branch in order to form the sural nerve (Figure T4). This nerve goes down and along the calcaneal tendon laterally in order to innervate the lateral edge of the foot through its terminal branch, the lateral dorsal digital nerve of the fifth toe. It can also split into three dorsal digital nerves to innervate the dorsal and lateral face of the fourth toe and the medial and lateral face of the fifth toe.

Terminal Branches

The tibial nerve divides into the lateral and medial plantar nerves under the medial malleolus and behind the flexor retinaculum (Figure T8). The plantar nerves then run in the plantar area, where they are first covered by the abductor hallucis muscle and the flexor digitorum brevis (Figures T7 and T8). The medial and lateral plantar arteries are situated between these two nerves. The former crosses the medial plantar nerve from above and distally. The medial plantar nerve goes in front and laterally under the tendons of the flexor digitorum longus muscle (Figures T7 and T8). It gives off three muscular branches for the muscles that it innervates: the abductor hallucis, the flexor digitorum brevis and flexor hallucis brevis muscles. It also gives off the medial and lateral plantar digital nerves of the hallux and of the second, third and fourth toes. The innervation of the fourth toe can also be partially managed by the sural nerve. The lateral plantar nerve goes ahead in front and laterally. It is crossed from below by the lateral plantar artery, which positions itself laterally. It is covered above by the muscle that it innervates and the quadratus plantae muscle and below by the flexor digitorum brevis. At the level of the fifth metatarsal, the lateral plantar nerve splits into its two terminal branches:

- The superficial branch goes towards the front and gives off muscular branches for the flexor brevis digiti minimi, opponens digiti minimi and abductor digiti minimi muscles and cutaneous branches for the lateral plantar face of the little toe and the fourth interosseous space with the fourth common plantar digital nerve.
- The deep branch is more medial and goes towards the front to innervate the muscles of the plantar interosseous spaces: the lumbrical muscles, the plantar interossei muscles, the dorsal interossei muscles and the adductor hallucis muscle.

Motor Function

Thanks to its collateral and terminal branches, the tibial nerve takes charge of the innervation of all the muscles of the posterior compartment of the leg (Figures T4 and T9): the tibialis posterior, the flexor digitorum longus and flexor hallucis longus as well as all the muscles of the plantar face of the foot—the flexor digitorum brevis, the lumbricals, the plantar interossei, the flexor digiti minimi brevis, the opponens digiti mini, the abductor digiti minimi and adductor hallucis. It is therefore responsible for the adduction, inversion, eversion and extension of the foot as well as the flexion, adduction and abduction of the toes.

Sensitive Function

The sensitive function of the tibial nerve is managed by its terminal branches, the medial and lateral plantar nerves, and by the tibial branch of the sural nerve (Figure T9).

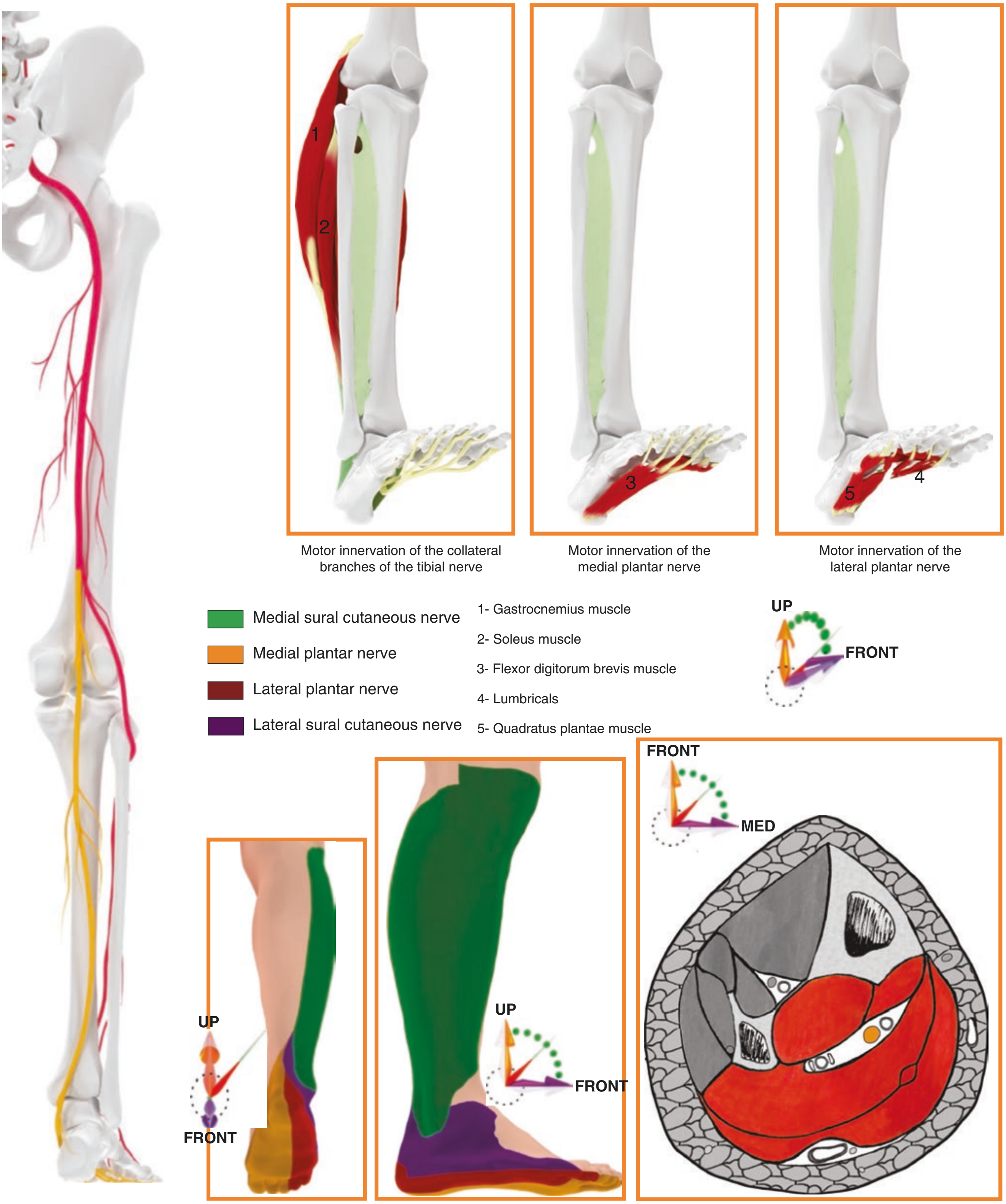
The sural nerve innervates the inferior part of the posterolateral face of the leg, under the territories of the posterior femoral cutaneous nerve and the lateral sural cutaneous nerves.

This territory extends until the lateral edge of the foot and the fifth toe.

The plantar nerves take charge of the whole sensitive innervation of the plantar face of the foot. The separation between their territories is generally situated at the level of the fourth toe. This distribution is similar to that of the innervation of the palmar face of the hand between the median and ulnar nerves.

Anastomoses

The most common anastomosis is the one composed of the medial sural cutaneous nerve and its homologous branch from the fibular nerve in order to make the sural nerve.



Motor innervation of the collateral branches of the tibial nerve

Motor innervation of the medial plantar nerve

Motor innervation of the lateral plantar nerve

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🟩 Medial sural cutaneous nerve
🟧 Medial plantar nerve
🟥 Lateral plantar nerve
🟪 Lateral sural cutaneous nerve
1- Gastrocnemius muscle
2- Soleus muscle
3- Flexor digitorum brevis muscle
4- Lumbricals
5- Quadratus plantae muscle
UP
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Figure T9. Motor and sensitive innervation of the tibial nerve.

The Tibial Nerve

1- Lateral sural cutaneous nerve

2- Peroneal communicating nerve

3- Medial sural cutaneous nerve

4- Saphenous nerve

5- Fibular nerve

6- Tibial nerve

7- Sural nerve

8- Deep fibular nerve

9- Superficial fibular nerve

10- Popliteal artery and vein

11- Great saphenous vein

12- Small saphenous vein

13- Anterior tibial artery

14- Fibular artery and vein

15- Posterior tibial artery

16- Patellar ligament of quadriceps femoris muscle

17- Tibia

18- Tibialis anterior muscle

19- Extensor digitorum longus muscle

20- Medial collateral ligament

21- Gracilis muscle

22- Sartorius muscle

23- Synovial bursa

24- Posterior cruciate ligament

25- Semimembranosus muscle

26- Fibula

27- Popliteus muscle

28- Lateral head of the gastrocnemius muscle

29- Plantaris muscle

30- Medial head of the gastrocnemius muscle

31- Extensor hallucis longus muscle

32- Flexor digitorum longus muscle

33- Posterior tibial muscle

34- Peroneus brevis muscle

35- Peroneus longus muscle

36- Soleus muscle

37- Flexor hallucis longus muscle

38- Calcaneal tendon

39- Triceps surae muscle

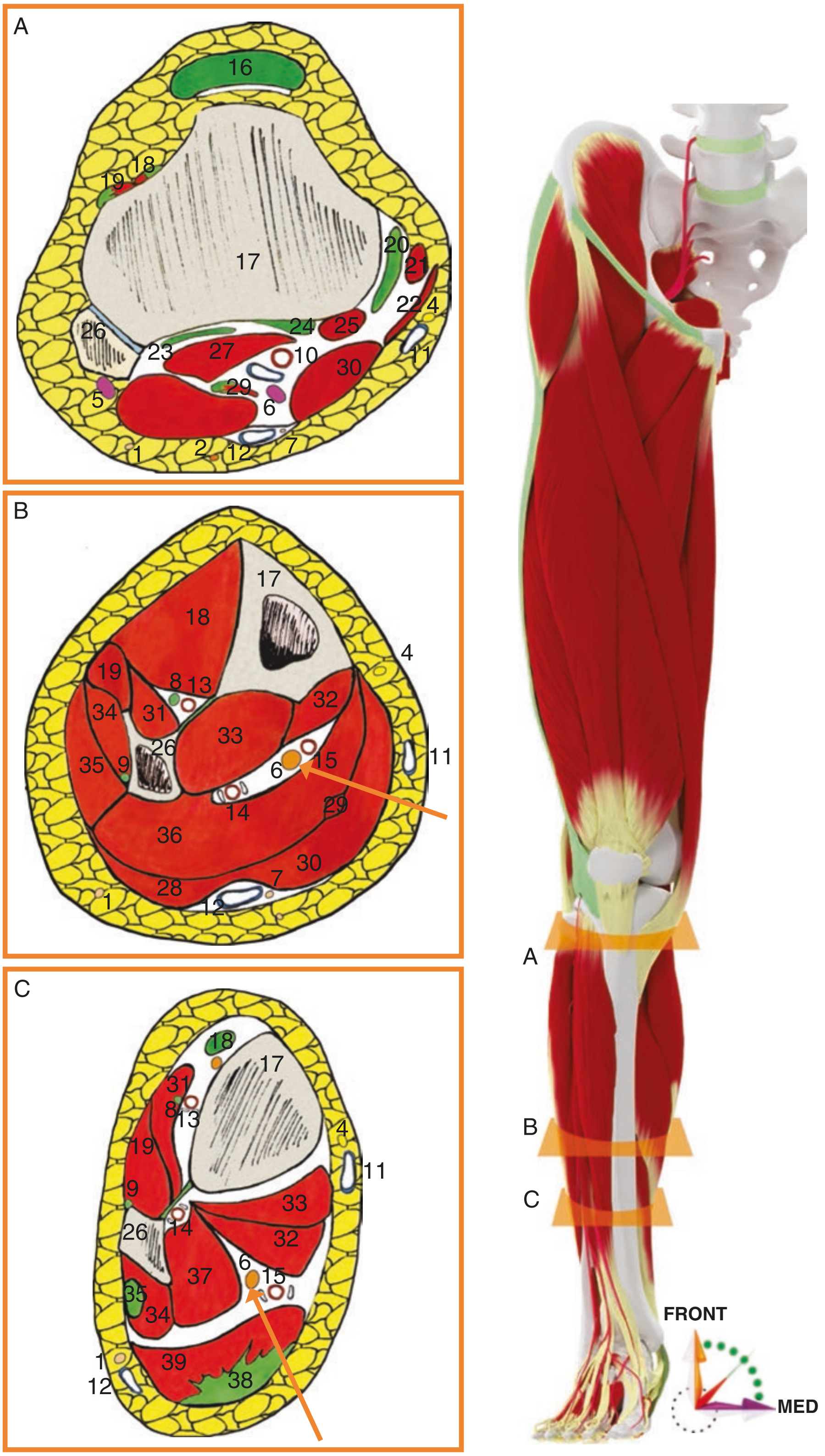
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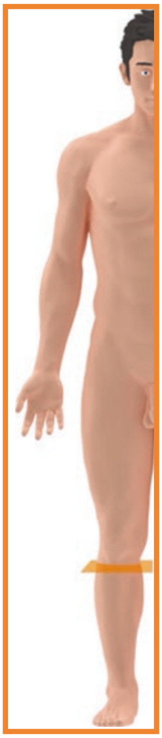
Figure T10. Relations of the tibial nerve in the leg, axial sections.



1- Patellar ligament

2- Deep infrapatellar bursa

3- Tibia

4- Fibula

5- Popliteus muscle

6- Common fibular nerve

7- Posterior tibial artery and vein

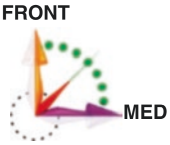
8- Tibial nerve

9- Great saphenous vein

10- Soleus muscle

11- Lateral head of gastrocnemius muscle

12- Medial head of gastrocnemius muscle



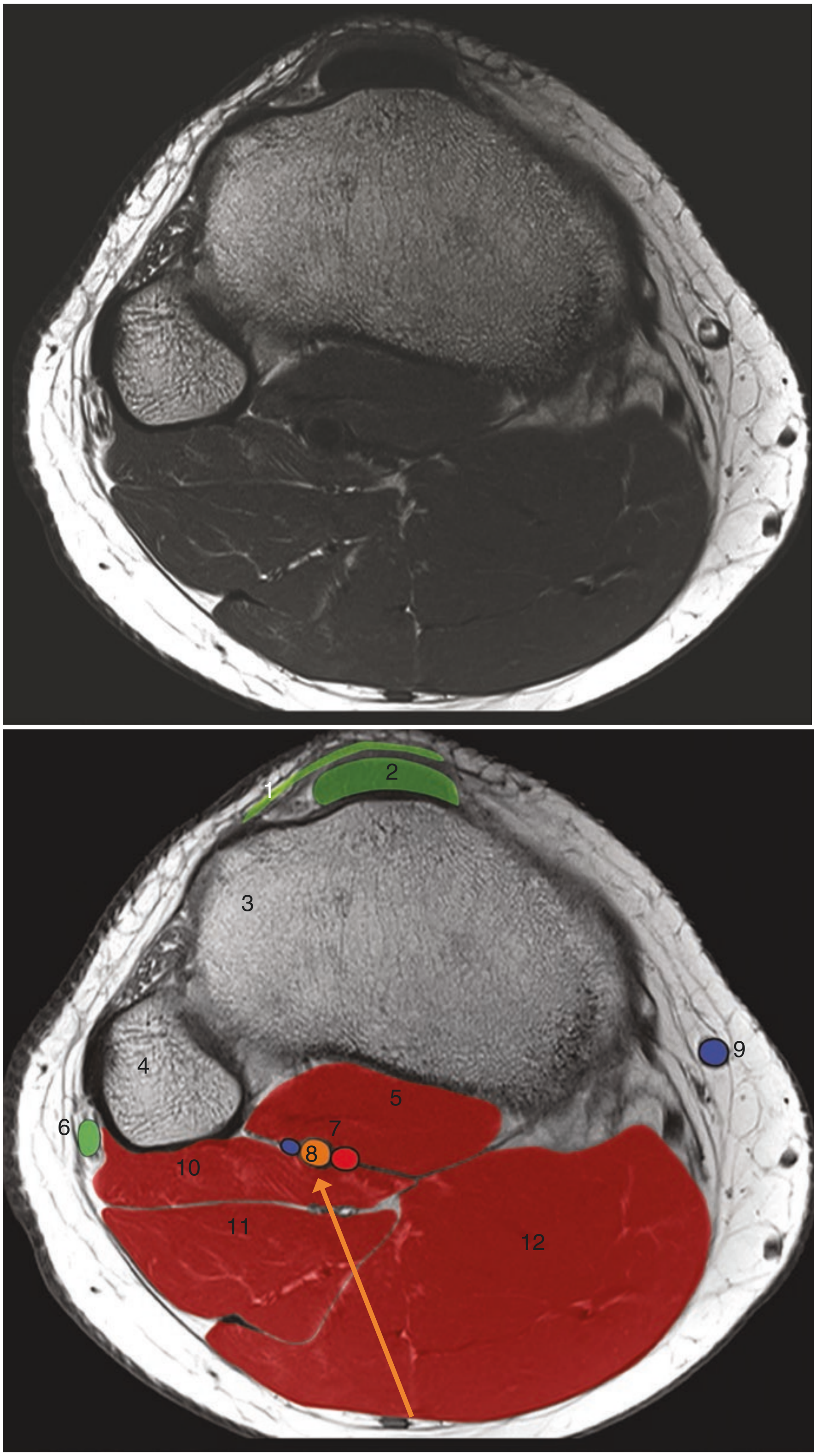
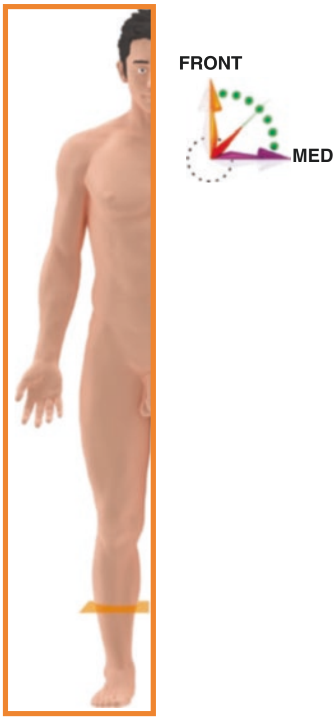
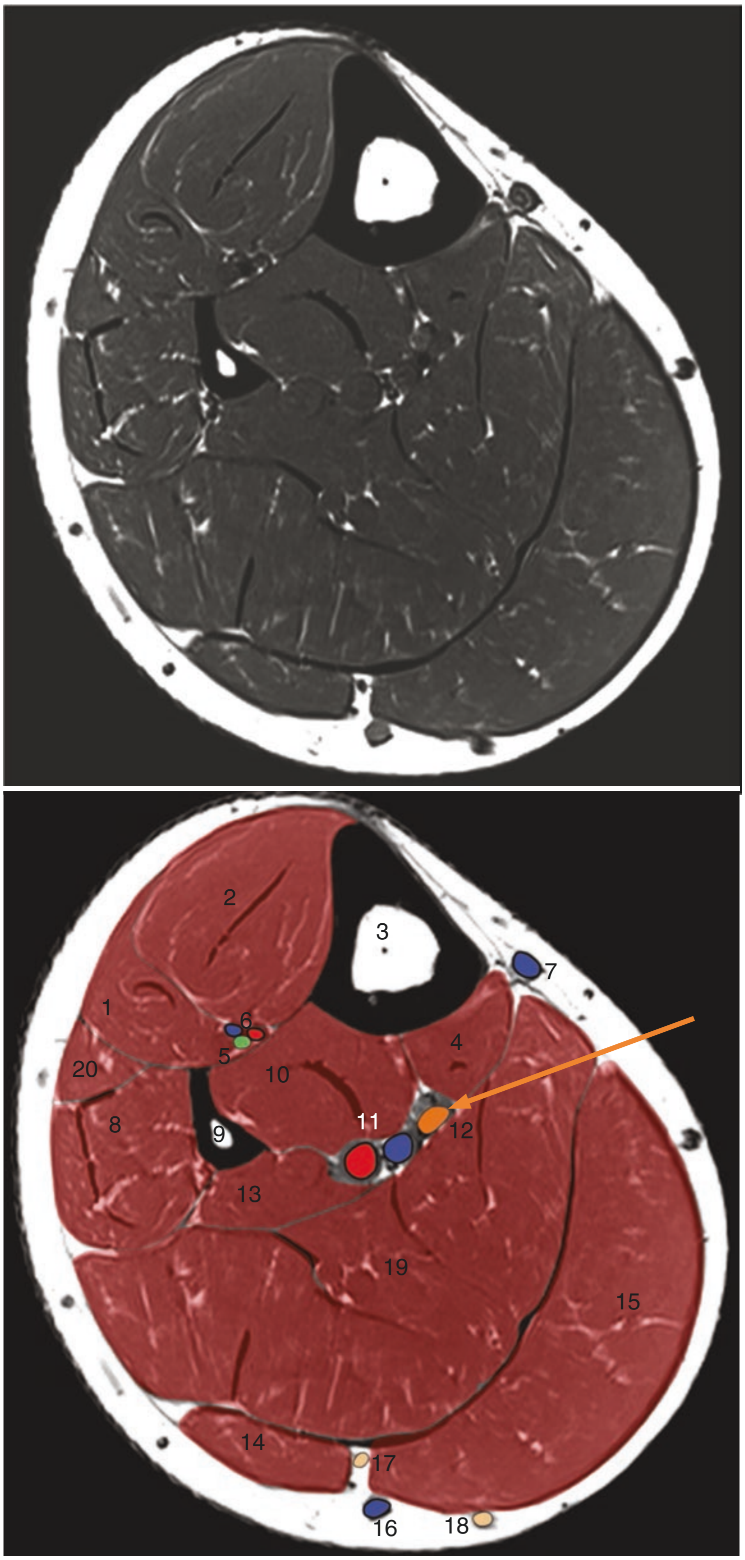


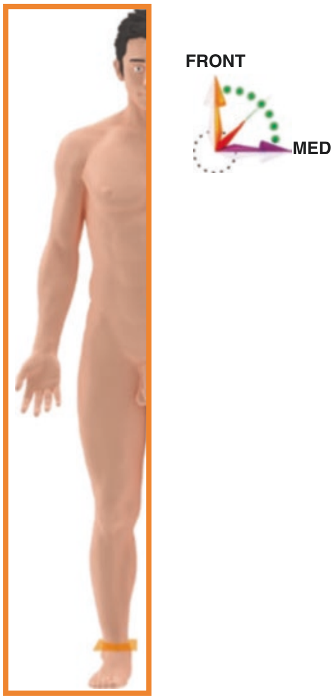
Figure T11. MRI scans at the proximal third of the leg through the tibial nerve.

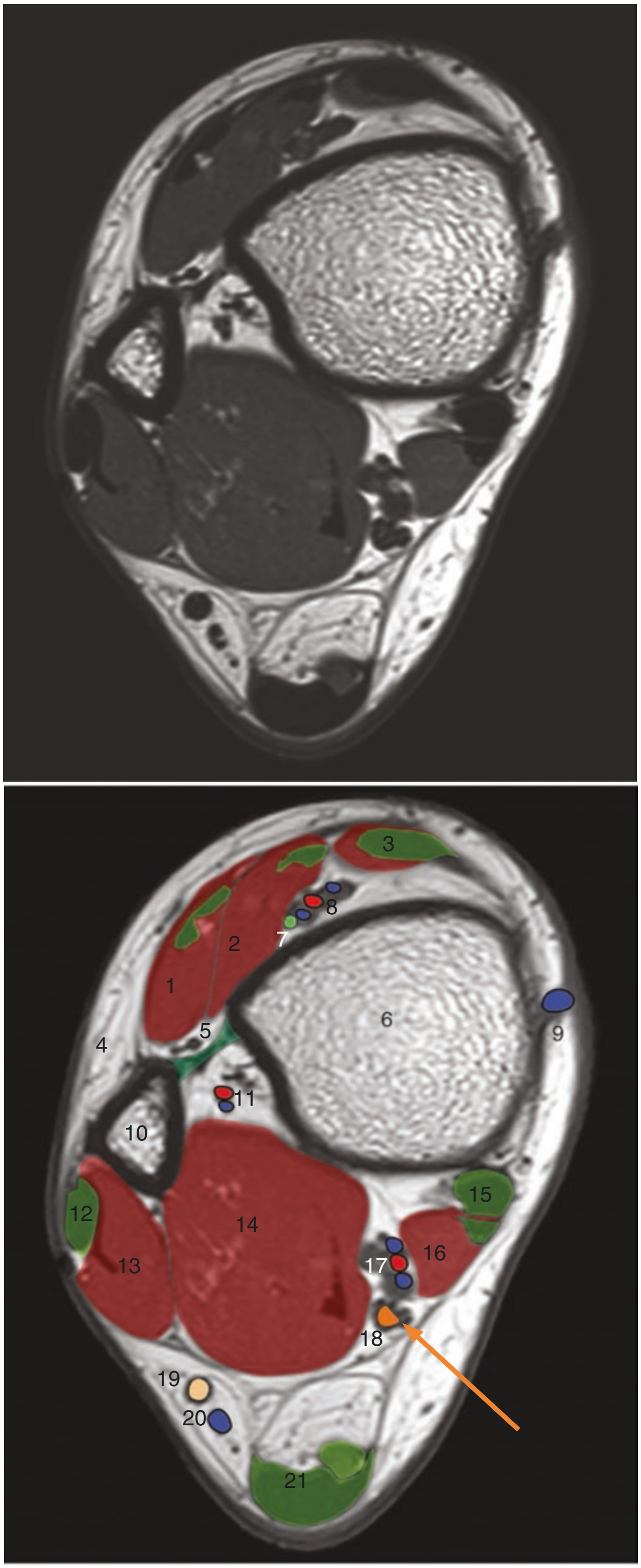




1- Extensor digitorum longus muscle
2- Tibialis anterior muscle
3- Tibia
4- Flexor digitorum longus muscle
5- Deep fibular nerve
6- Anterior tibial artery and vein
7- Great saphenous vein
8- Peroneus longus and brevis muscles
9- Fibula
10- Posterior tibial muscle
11- Posterior tibial artery and vein
12- Tibial nerve
13- Flexor hallucis longus muscle
14- Lateral head of gastrocnemius muscle
15- Medial head of gastrocnemius muscle
16- Small saphenous vein
17- Medial sural cutaneous nerve
18- Sural nerve
19- Soleus muscle
20- Extensor hallucis longus muscle

Figure T12. MRI scans at the distal third of the leg through the tibial nerve.





1- Extensor digitorum longus muscle

2- Extensor hallucis longus muscle

3- Tendon of the tibialis anterior muscle

4- Superficial fibular nerve

5- Interosseous membrane

6- Tibia

7- Deep fibular nerve

8- Anterior tibial artery and vein

9- Great saphenous vein

10- Fibula

11- Fibular artery and vein

12- Tendon of the peroneus longus muscle

13- Peroneus brevis muscle

14- Flexor hallucis longus muscle

15- Tendon of the posterior tibial muscle

16- Flexor digitorum longus muscle

17- Posterior tibial artery and vein

18- Tibial nerve

19- Sural nerve

20- Small saphenous vein

21- Tendons of the triceps surae and plantaris muscles

Figure T13. MRI scans in the ankle through the tibial nerve.

Pathology

Soleus Syndrome

In the leg, the tibial nerve goes under the tendinous arch of the soleus muscle. This arch can compress the tibial nerve in diverse circumstances. It is therefore a true entrapment neuropathy.

Aetiology

- Compression: This entrapment neuropathy can happen on the posterior face of the leg. However, a pure entrapment neuropathy remains rare, and it is important to look for another cause using an appropriate imagery technique (echography or MRI), especially the presence of an articular ganglion cyst or of a tumour (Figure T14).

Clinical Significance

- Sensitive signs: The patient complains about a stabbing, sharp pain originating from the upper part of the posterior face of the leg. Tinel's sign can be found at the level of the tendinous arch of the soleus muscle, awakening the pain.
- This pain can be worsened by a flexion of the foot on the leg, mimicking Homans' sign (the differential diagnosis being deep vein thrombosis). A hypoesthesia settles on the territory of the tibial nerve, without affecting that of the sural nerve. It therefore concerns a territory in the shape of a triangle with an upper vertex going towards the lower part of the calf, the heel and the sole of foot.
- Motor signs: In addition to the previously described deficits, there is also a denervation of the muscles of the posterior compartment of the leg that can lead to disuse atrophy. At first, the patient can no longer stand on tiptoes.

Then, the patient's Achilles reflex becomes absent, and, eventually, as mentioned above, a disuse atrophy of the posterior compartment of the leg can appear.

Explorations

- An electroneuromyography gives little to no information in a case of pure entrapment neuropathy.
- MRI is the examination of choice for searching for an extrinsic compression cause.

Treatment

If there is no compression element open to etiological treatment, the treatment should be conservative: bed rest and work on improvement of the patient's posture in order to isolate pain-relieving attitudes, physiotherapy, etc. If a genuine compression of the tibial nerve is brought to light, the tendinous arch of the soleus muscle should be sectioned if it is a pure entrapment neuropathy, whilst resection surgery should be favoured if a compression injury is seen on the imagery.

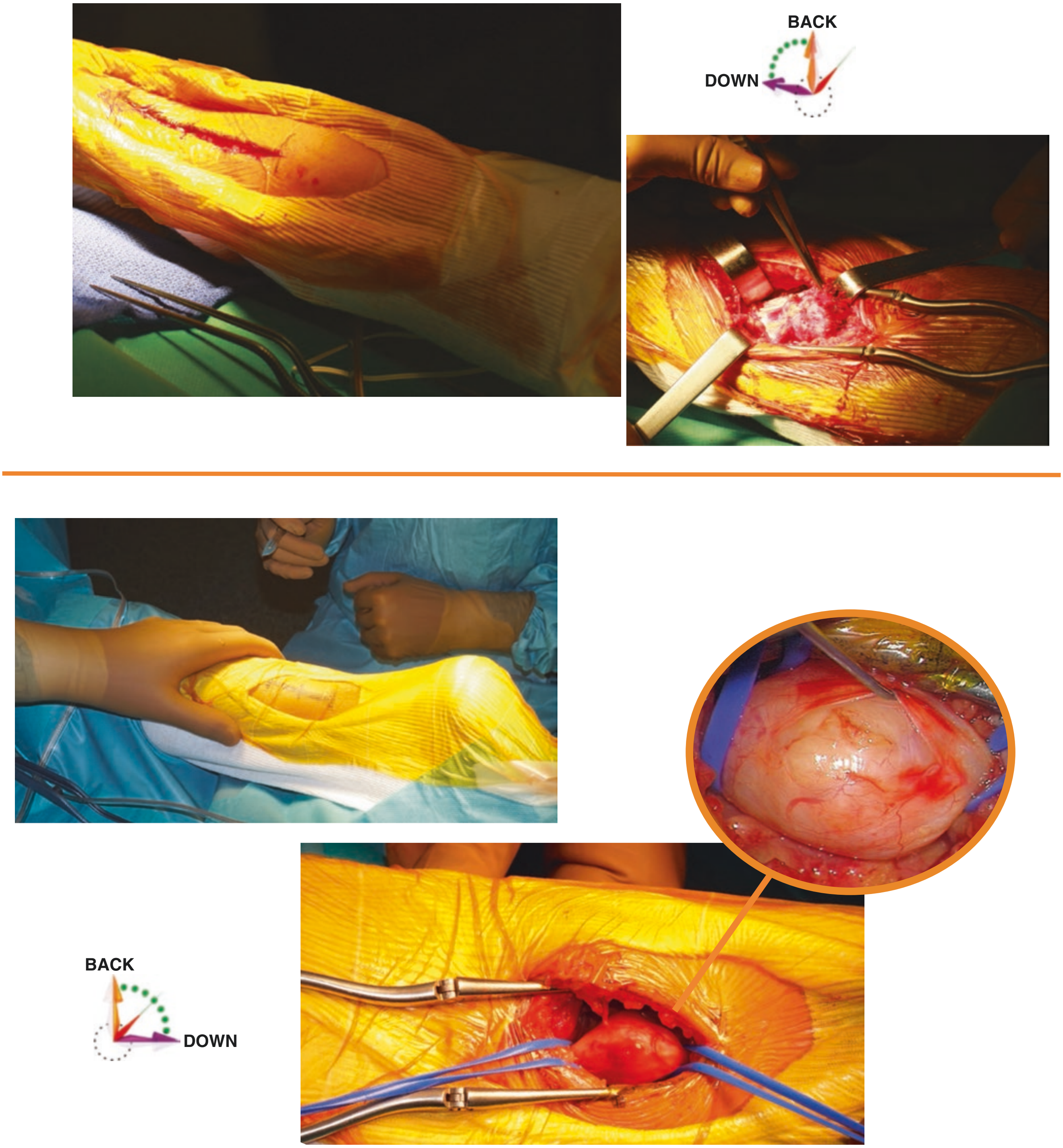


Figure T14. Removal surgery of a schwannoma at the level of the popliteal fossa (*above*) and the posterior compartment of the leg (*below*). The latter was generating neuropathic pain sensations on the lower part of the calf and at the level of the arch of the foot in the right leg.

Tarsal Tunnel Syndrome

This is the equivalent of carpal tunnel syndrome for the lower limb, although much less frequent.

The tibial nerve goes under the medial malleolus, in the flexor retinaculum, accompanied by the posterior tibial veins and arteries. It generally divides at this level into two branches: the medial and lateral plantar nerves. In this tunnel, the vessels are superficial in relation to the nerve.

Aetiology

This is a true entrapment neuropathy where the tibial nerve is compressed. Traumatic factors can favour its apparition such as post-traumatic deformity, excessive sports activity or an expansive process inside the canal.

Clinical Significance

- Sensitive signs: Pain, paraesthesiae or even a “burning” sensation in the foot concerning the sole of the foot and/or the heel (Figure T15). These territories correspond to injury of the medial and lateral plantar nerves.

  These sensations are sometimes replaced by numbness, with an increase of the symptoms during night-time.

  The patient lets their foot hang outside of the bed, relieved by a varus position. The pain can be evoked by performing Tinel’s sign under the medial malleolus.

  The differential diagnosis must eliminate a pain originating from arteritis. If the nerve division is situated in a higher position, the area of pain can only reach as far as the heel.
- Motor signs: The tibial nerve innervates all of the muscles of the plantar face of the foot. A deficit can happen belatedly in the extension of the toes, the flexion of the foot and the inversion of the foot. A paresis of the intrinsic muscles of the foot can sometimes exist.

Clinical Forms

A general check-up should look for history of micro- or macro-traumas, tenosynovitis, rheumatoid polyarthritis, dialysed kidney failures, vein thrombosis, varicose veins and all other elements that may have an aetiological influence and can necessitate a specific treatment.

Explorations

- An electroneuromyography confirms the diagnosis in most cases, whilst an echo Doppler eliminates the possibility of a vascular pathology if doubt remains.
- Radiographies allow for the evaluation of the general skeleton status.
- An MRI can be performed when searching for associated pathologies, especially for an intrinsic injury of the nerve (tumour, intraneural cyst injury, etc.) or for a muscle anomaly (Figure T5).

Treatment

Conservative treatment includes local infiltrations. It depends on the eventual presence of a trigger factor.

Surgical treatment gives the best results: 98% of good or excellent results after 1 year, with less than 1% of recurrence in pure entrapment neuropathy cases. Surgery consists of cutting the retinaculum at the internal face of the malleolus in order to release the nerve (Figure T16).

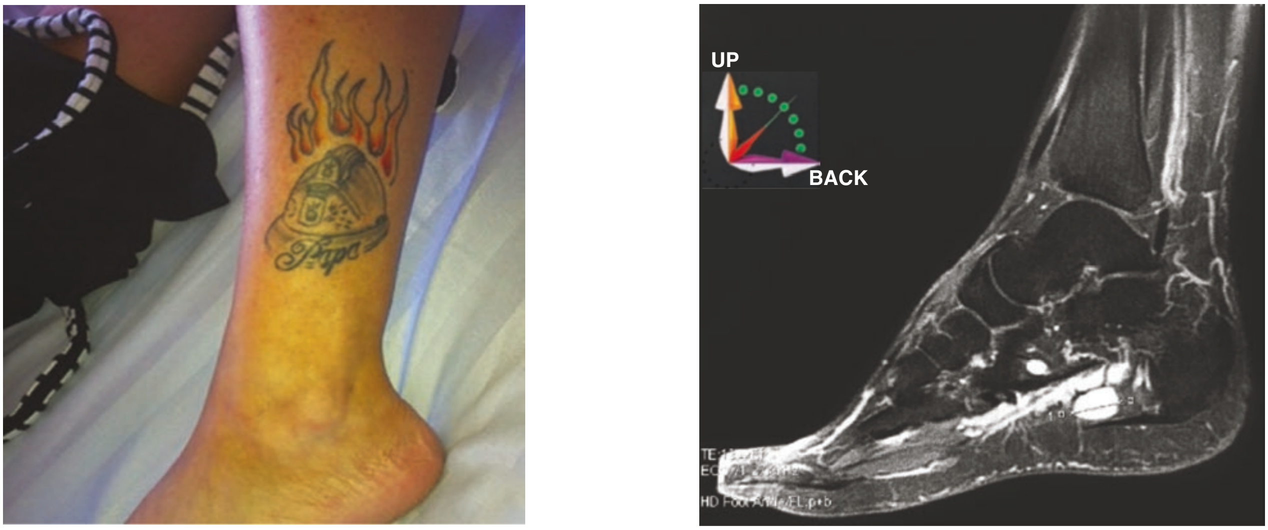


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Figure T15. Case of a patient showing proven neuropathic pain sensations at the sole of the foot. The MRI highlights a string of schwannoma-type injuries along the branches of the plantar nerves.

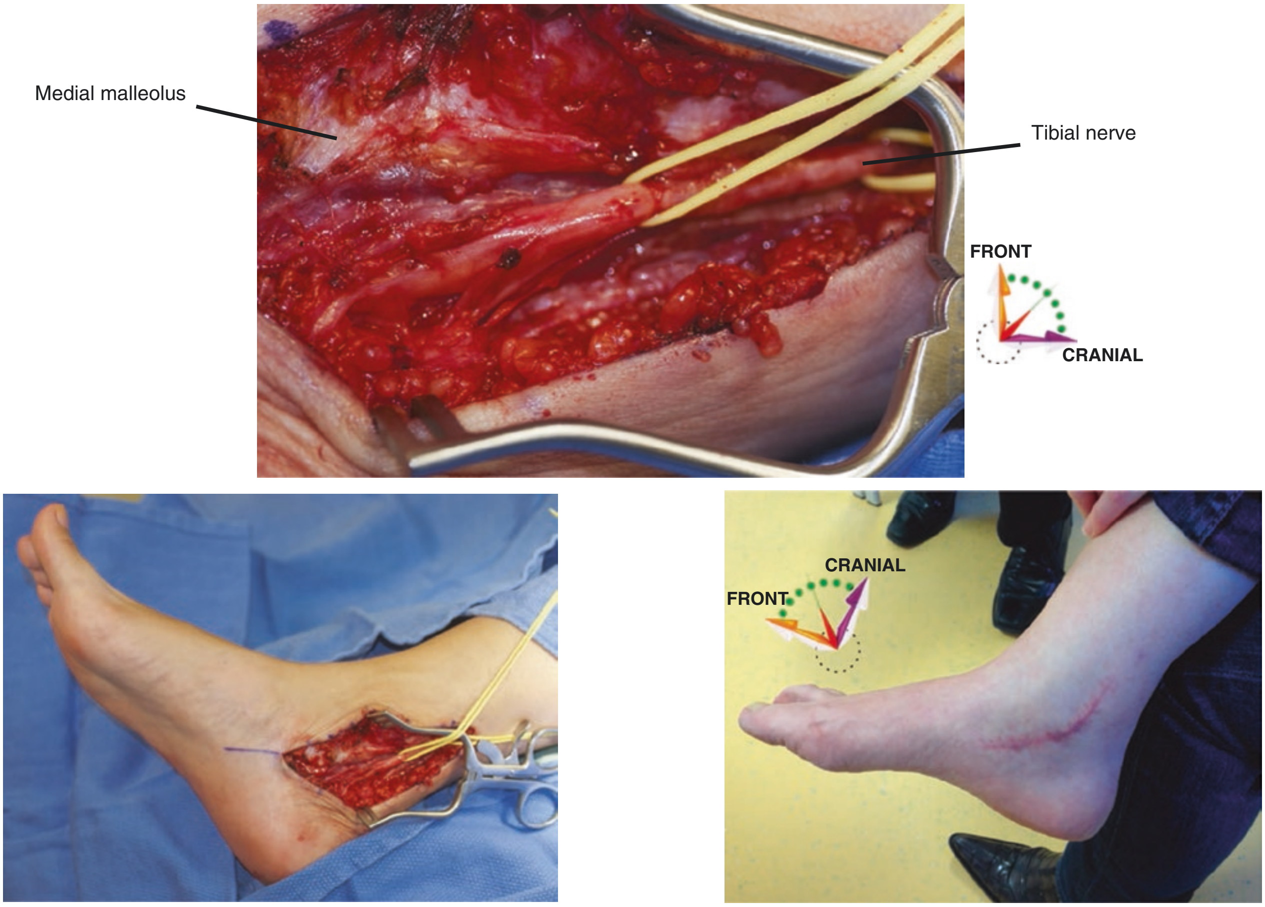
Medial malleolus
Tibial nerve
FRONT
CRANIAL
CRANIAL
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Figure T16. Diagrams of the pathology of the tibial nerve and surgical approach in the ankle.

Morphological Data: Sono Anatomy

At the popliteal fossa, the tibial nerve is located under the popliteal fascia.

At the upper part of the pit, it is found between the semimembranosus and semitendinosus muscles (medially) and the biceps femoris muscle (laterally).

At the lower part of the popliteal fossa, it is lateral to the medial chief of the gastrocnemius muscle and medial to the lateral chief of the gastrocnemius muscle and to the plantaris muscle.

The nerve emits usually five collaterals in the heart of this pit, branches for the medial and lateral leaders of the gastrocnemius muscle, the plantaris muscle (most cranial branch), the soleus muscle and the popliteus muscle (most caudal branches). It then travels under the arch of the flexors to the anterior and lateral edge of the tendons of the flexors of the foot, in the malleolar direction.

In the distal quarter of the leg, the nerve passes behind and under the medial malleolus, between the flexor hallucis longus medially, the flexor digitorum longus tendon in front and the crural fascia in back. It then enters the tarsal tunnel at the foot level. The posterior tarsal tunnel is a narrow osteofibrous tunnel located between the flexor retinaculum, the tendon of the abductor hallucis and a lateral bone wall bounded by the medial faces of the talus and calcaneus.

Classically, the tibial nerve is divided at this level into two terminal branches: the medial plantar and lateral nerves.

Installation

The patient can be installed:

- In supine position with external rotation of the lower limb and flexion of the knee, so as to better expose the medial surface of the leg to the practitioner
- In prone position
- In lateral decubitus by installing the limb being ultrasonographed as close as possible to the operator

Equipment and Location

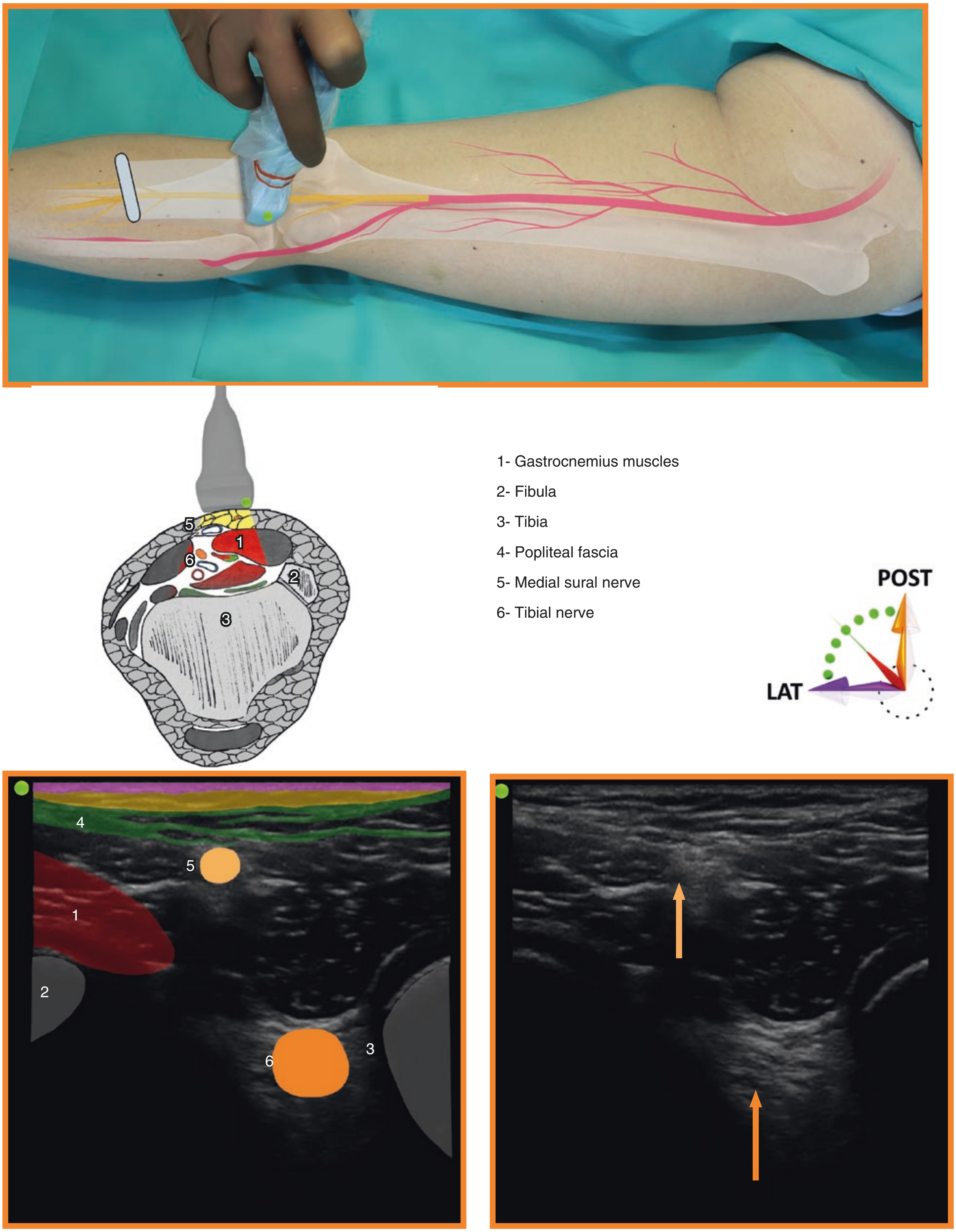
- Probe type: linear, high frequency
- Probe axis: axial/transverse

Ultrasound Procedure

The probe is placed in the axial plane, to obtain a cross-sectional image of the tibial nerve and the attached tibial artery. The probe is ideally positioned according to the echogenic characteristics of the patient, generally behind and at the proximal part of the medial malleolus. On the standard ultrasound section, we can see the vessels and nerves placed on the deep face of the superficial fascia, crimped backwards by the calcaneal tendon or distal part of the triceps surae and further down by the flexor hallucis longus and flexor digitorum longus muscles. Given the size of the probe, it is common to use a puncture outside the ultrasound plane in order to avoid grazing the medial surface of the tibia or crossing the calcaneal tendon.

Many veins are present in the tarsal tunnel, which are identified by pressure/depression movements and using colour Doppler to highlight them.

Sometimes it is difficult to differentiate the tibial nerve and tendon from the flexor hallucis longus, so it is possible to ask the patient to flex the big toe, and the flexor digitorum longus muscle will mobilize and not the tibial nerve (Figures T17–T19).



1- Gastrocnemius muscles
2- Fibula
3- Tibia
4- Popliteal fascia
5- Medial sural nerve
6- Tibial nerve

Figure T17. Ultrasound transversal views of the tibial nerve at the popliteal level, before its collateral branches distribution.

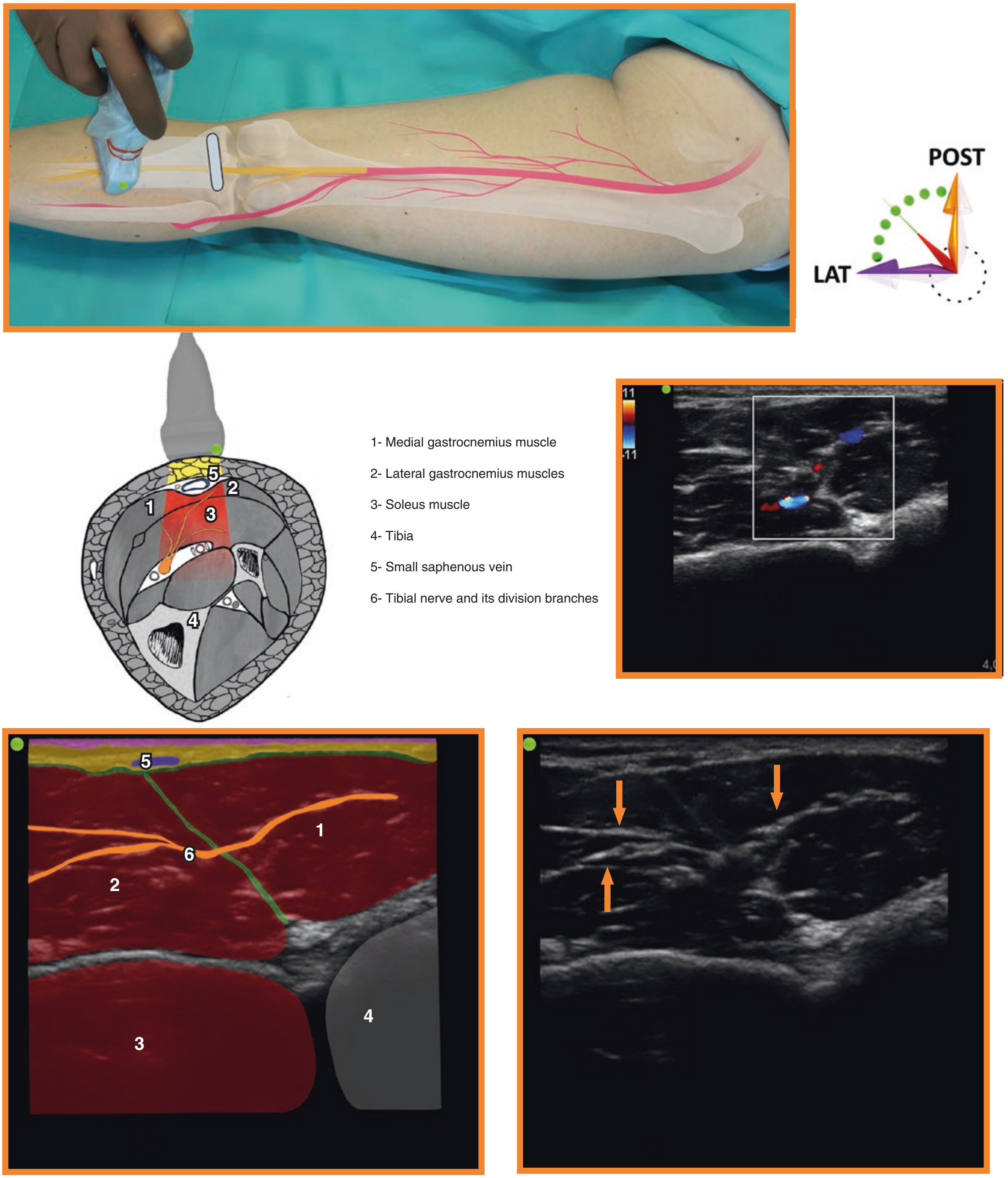

POST
LAT
1- Medial gastrocnemius muscle
2- Lateral gastrocnemius muscles
3- Soleus muscle
4- Tibia
5- Small saphenous vein
6- Tibial nerve and its division branches
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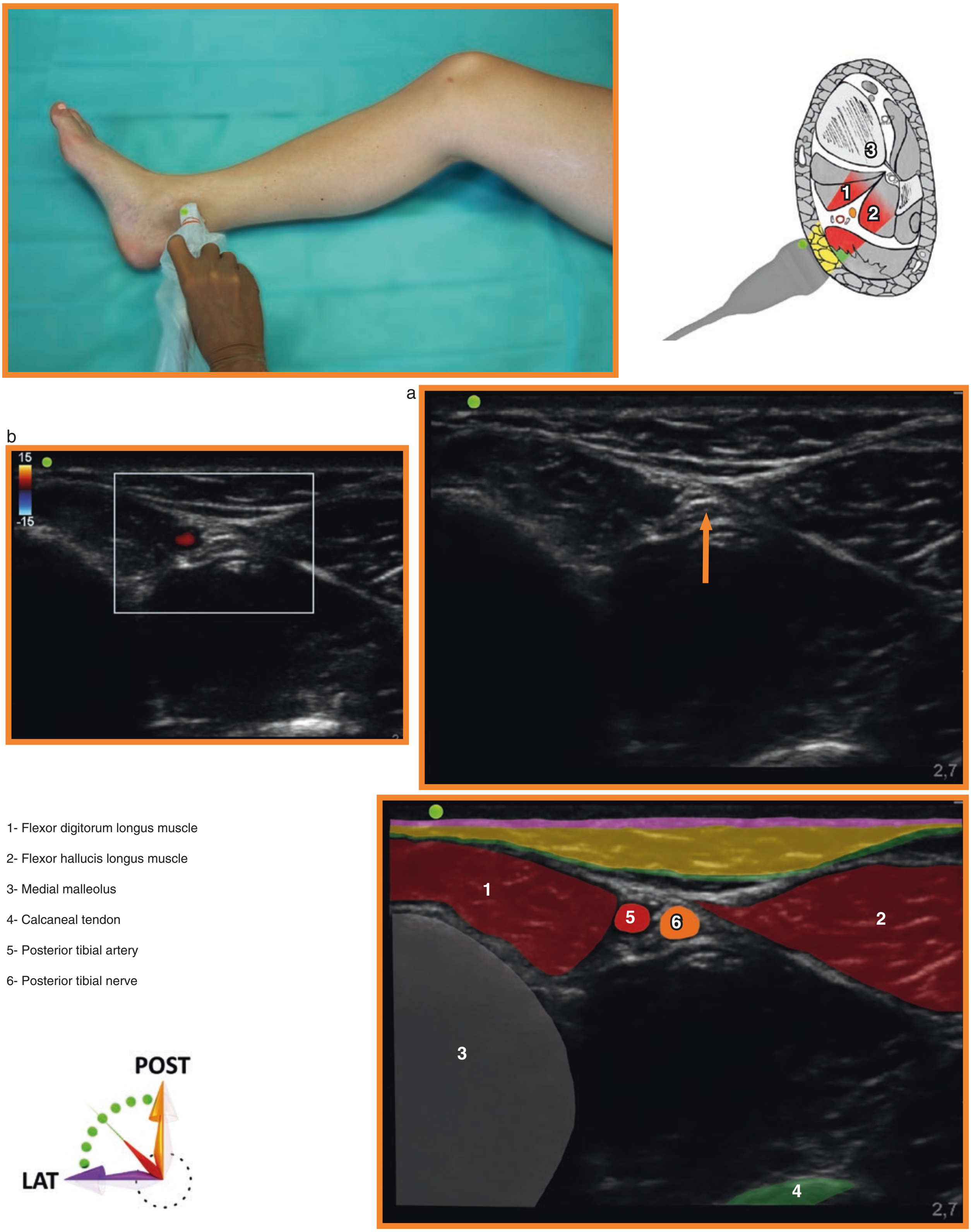
Figure T18. (**a**) Ultrasound transversal views of the tibial nerve and its division into gastrocnemius, soleus and plantaris muscles. (**b**) Doppler mode view.



1- Flexor digitorum longus muscle
2- Flexor hallucis longus muscle
3- Medial malleolus
4- Calcaneal tendon
5- Posterior tibial artery
6- Posterior tibial nerve

Figure T19. (**a**) Ultrasound transversal views of the tibial nerve at the posterior tarsal tunnel level. (**b**) Doppler mode view.

Interventional Procedure

Infiltration/Test Block

Infiltration at the Proximal Part of the Tibial Nerve

Indication

The main indication is the performance of anaesthesiological blocks of the lower limb, under ultrasound, as part of multidisciplinary management of disability and spasticity.

The aim is to distinguish between retraction and spasticity when a hemiplegic spastic patient has an equine varus deformity of the foot.

This block can be more or less selective depending on the level at which it will be carried out:

- It may involve the tibial trunk as a whole, above the popliteal fossa, and the block will then be intended for the posterior compartment of the triceps surae muscle, the tibialis posterior muscle and the trunk of the flexors.
  - On the other hand, it can be more distal, once the branches for the triceps surae muscle and tibialis posterior muscle are unchecked, and it will be selective on the trunk of the flexors, including at this level the branches for the flexor digitorum longus and the flexor digitorum brevis muscles. The purpose of this block will be to make a distinction between retraction and spasticity in the context of a toe claw.
- If the operator wishes to further investigate, to distinguish between claws related to the intrinsic or extrinsic muscles of the foot, he can then start with an ultra-selective block of the tibial nerve at the ankle and then secondarily complete it with a block of the trunk of the flexors further upstream.
- Finally, when the problem is not centred on the varus but rather on the equinus, the operator may decide to block the soleus nerve and/or one of the gastrocnemius nerves ultra-selectively. For the analysis of the varicating component and to make a distinction between a forefoot and hindfoot varus, the block can be used ultra-selectively on the nerve of the tibialis posterior muscle if necessary (Figure T20).
- If neurotomy is indicated, a preoperative simulation of the percentage of fibres that will need to be resected can sometimes be indicated, and care should be taken to perform a nerve block of a particular branch, at a minimum, or a sub-total block, or a total block, if necessary (Figure T20).

Technique

The in-plane technique will be preferred to have permanent visual control of the needle tip, given the proximity of the vascular axes.

We will not describe an interventional procedure such as implantation of peripheral nerve stimulation on the tibial nerve at this level.

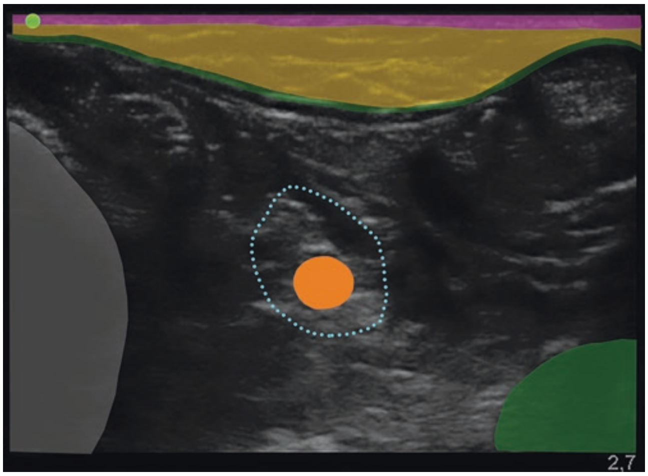


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Figure T20. Some illustrative views of tibial nerve infiltration at the proximal part.

The Tibial Nerve

Infiltration of the tibial nerve at the ankle, at its retro-malleolar internal portion.

Indication

Three indications can lead us to perform a distal tibial nerve block:

- The first involves refractory neuropathic distal foot pain.
- The second involves a need for diagnostic confirmation of posterior tarsal tunnel syndrome.
- The third indication, as mentioned above, involves creation of differential and ultra-selective blocks of the tibial nerve to distinguish between a toe claw linked to hypertonicity of the muscles not extrinsically but intrinsically to the foot.

Technique

- The patient is placed in supine position, with the lower limb slightly in external rotation, to optimize exposure of the retro-malleolar part of the foot.
- Plantar flexion is indifferent.
- The probe used is a superficial, linear, high-frequency, space-saving, hockey stick-type probe.
- The out-of-plane po sition will be preferred because, otherwise, the operator would be hindered by malleolar bone structures and on the other side by the calcaneal tendon.
- The nerve will be placed in the centre of the screen, as usual.

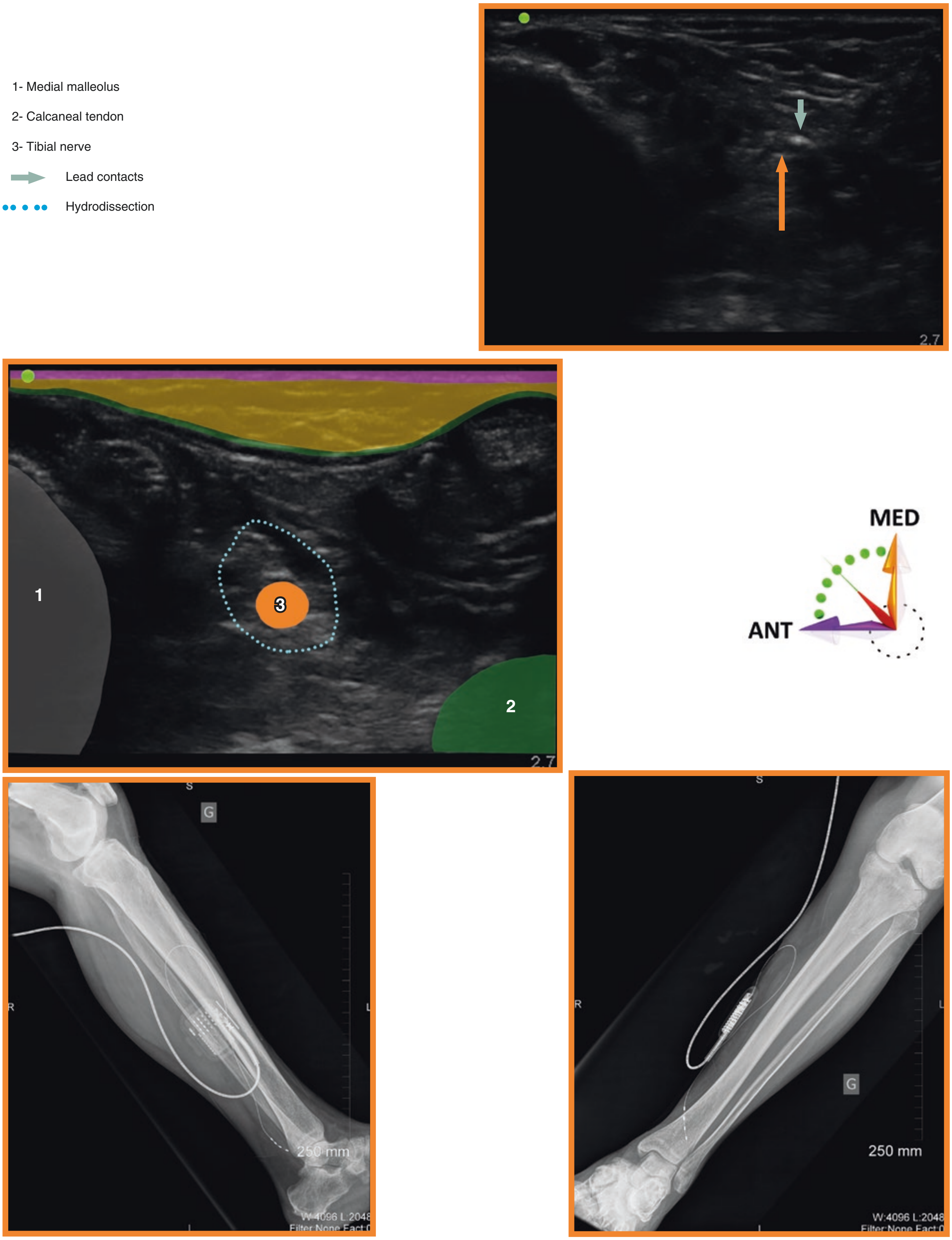
RFP

We do not have the experience of RFP in this indication given the essentially motor nature of this nervous trunk.

PNS

After ultrasound identification of the nerve, the lead will be positioned upstream of the posterior tarsal tunnel given the risk of secondary mobilization of the lead, given the high regional mobility at this level.

The lead stimulation will be inserted by means of an out-of-plane marking and hydrolocalization. Confirmation of the lead location will be recorded by visualizing the lead in contact with the nerve. A sensitive or even motor stimulation can be used for the ultimate confirmation of the quality and selectivity of the stimulation (Figure T21).


1- Medial malleolus
2- Calcaneal tendon
3- Tibial nerve
Lead contacts
Hydrodissection
2.7
1
3
2
2.7
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ANT
S
G
R
L
250 mm
W:4096 L:2048
S
R
L
G
250 mm
W:4096 L:2048

Figure T21. Some illustrative views of tibial nerve neurostimulation. (**a**) Ultrasound guidance. (**b**) Post-op X-ray showing the lead positioning at the entry of the posterior tarsal tunnel.

Sural Nerve

The sural nerve is formed by the combination of a branch of the tibial nerve (medial sural nerve) and a branch of the fibular nerve (lateral sural nerve). It is accompanied by the small saphenous vein between the Achilles tendon and the lateral malleolus. In general, the sural nerve is more medial or posterior than the small saphenous vein.

Installation

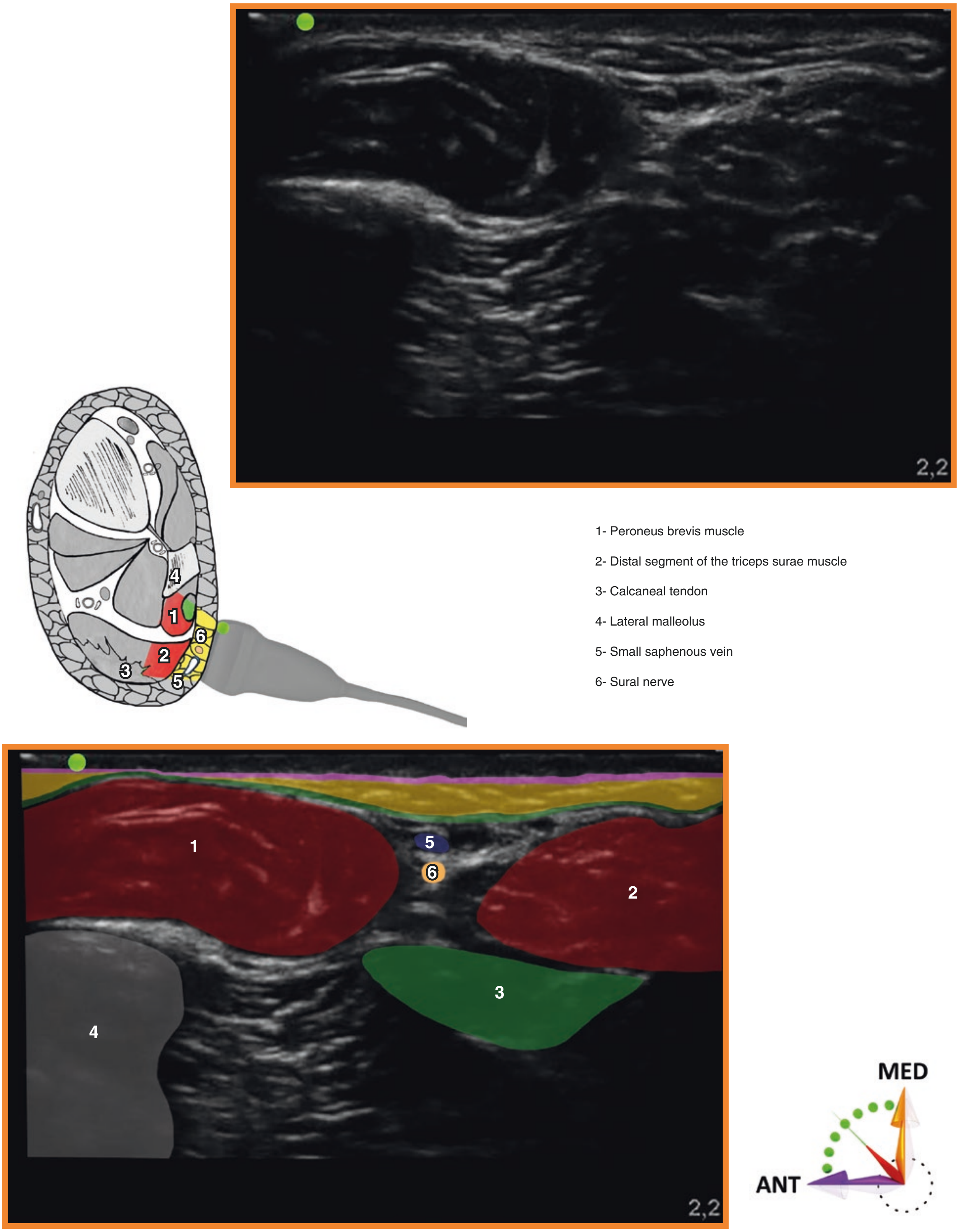
The patient is in lateral decubitus, lying on the side not involved by the procedure.

Equipment and Location

- Type of sensor: linear, high frequency, if possible hockey stick-type sensor
- Probe axis: transverse/axial

Ultrasound Procedure

The probe is positioned in the axial plane, at the upper end of the lateral malleolus and slightly behind it, to visualize the space between the calcaneal tendon (back) and the fibula (front). The sural nerve is visualized at this level, a satellite of the small saphenous vein in its ventral portion. The specific interest of compression/decompression manoeuvres to identify vascular structures, essential for localization of this nerve, should be noted (Figure T22).



1- Peroneus brevis muscle
2- Distal segment of the triceps surae muscle
3- Calcaneal tendon
4- Lateral malleolus
5- Small saphenous vein
6- Sural nerve

Figure T22. Ultrasound transversal views of the sural nerve at the ankle level.

Infiltration/Test Block

Indications

Neuropathic pain in the lateral surface of the foot.

Technique

After ultrasound identification of the sural nerve as described above, the infiltration needle is positioned "in plane". The direction of the puncture will be posterior–anterior given the prominence of the lateral malleolus (Figure T23).

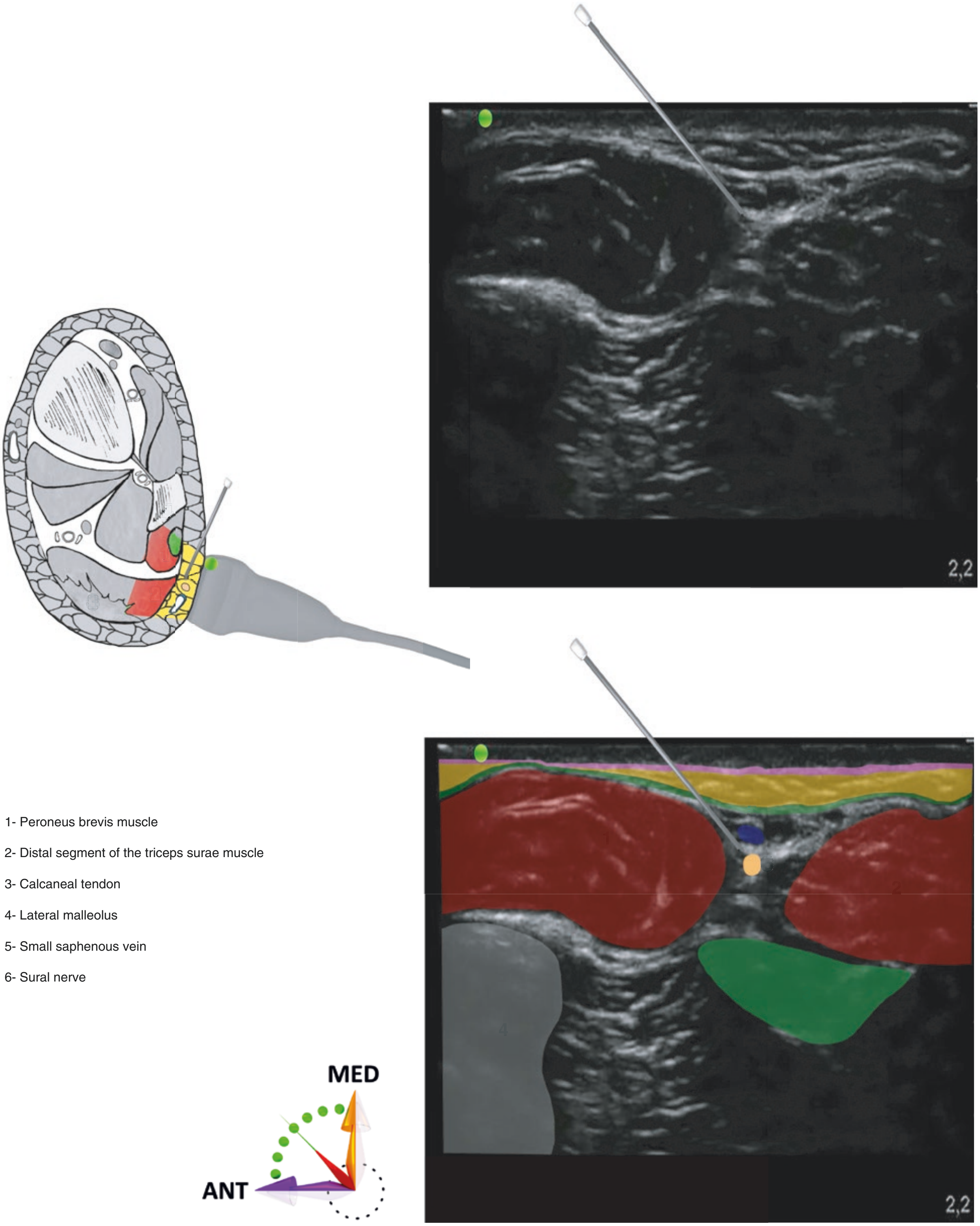
RFP

Indication

Positive test block but of fleeting effectiveness in refractory neuropathic pain of the lateral surface of the foot.

Technique

After ultrasound identification of the sural nerve as described above, the stimulation needle is positioned "in plane". It is necessary to work in the ultrasound plane in order to properly locate the end of the stimulating needle. The stimulation rules remain classic; the stimulation test is carried out with the following parameters: 1 ms, 50 Hz, <0.45 V, then the radiofrequency is carried out at 2 ms, 45 V to reach a temperature rise of the thermocouple <42 °C.



1- Peroneus brevis muscle

2- Distal segment of the triceps surae muscle

3- Calcaneal tendon

4- Lateral malleolus

5- Small saphenous vein

6- Sural nerve

Figure T23. Sural nerve anaesthetic block (in place technique).

Surgical Procedure

Surgical Indications

In the Leg

Selective tibial neurotomy, in the treatment of spastic equine varus feet, most often associated with neuro-orthopaedic gestures such as an extension of the Achilles tendon, a Castaing procedure to laterally stabilize the ankle, a tibialis anterior hemitransplant and/or a section of the flexor digitorum longus muscle.

Skin Incision

It differs from school to school. Some propose a minimalist transverse incision at the posterior fold of the knee, others recommend a vertical incision making a "bayonet" opposite the fold in question and others, finally, propose an arciform incision starting from the inner edge of the lower third of the thigh or fold and then curved and ending at the lateral edge of the upper third of the leg outside the gastrocnemius lateral muscle (Figure T24) (minimal incision is reserved, in case of neurotomy, to surgeons with a three-pole electrode stimulation).

Nervous Exposure

After removing subcutaneous fat, the aponeurosis will be incised outside the short saphenous vein, itself outside the medial sural cutaneous nerve. The biceps femoris muscle (inside) of the semitendinosus muscle (outside) is clipped upwards, the inter-gastrocnemius lodge is crossed to laterally reflex them and approach the tibial nerve in contact with the deep vessels (Figure T25). The motor branches of the tibial nerve are then easily discovered in the lower part of the popliteal fossa by identifying the branches of the gastrocnemius muscles, the upper and lower nerves of the soleus, the branches of the popliteus muscle and the nerve of the tibialis posterior muscle. The residual contingent of the nerve will then penetrate the arch of the flexors a little lower, by unchecking their branches with a driving purpose.

Technical Pitfalls

- Excessive interruption of distal venous drainage (postoperative oedema of the limb)
- Anatomical variations of the soleus and tibialis posterior branches
- Vascular lesion of the popliteal axis at the leg and tibial arteries at the ankle

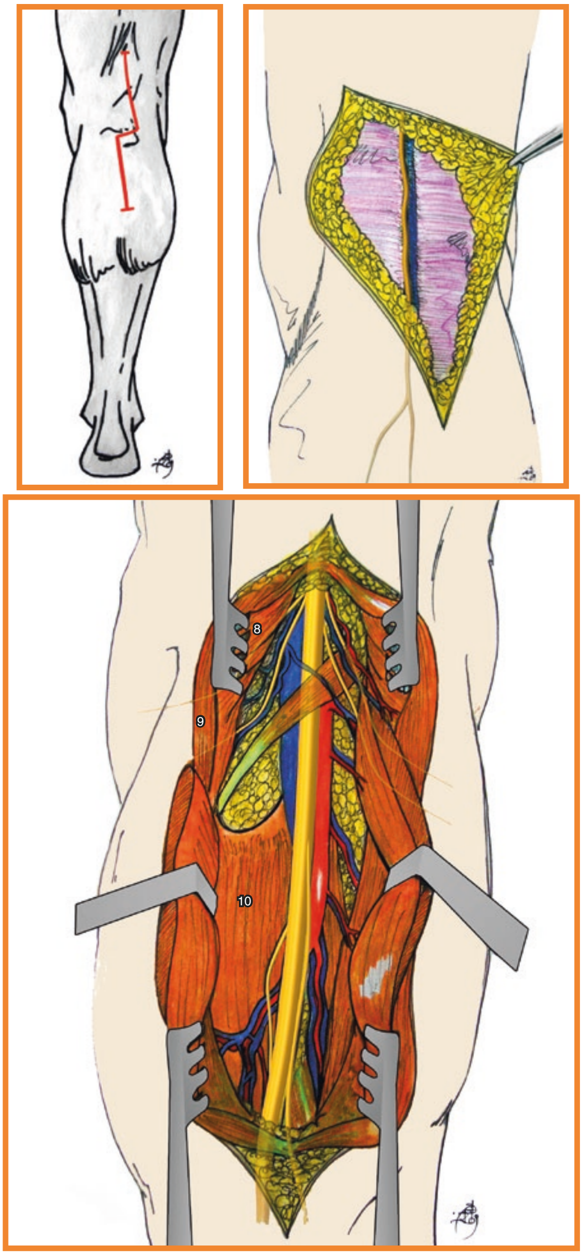


Figure T24. Surgical approach of the tibial nerve at the popliteal fossa level.

1- Sciatic nerve

2- Tibial nerve

3- Lateral sural cutaneous nerve

4- Popliteal artery

5- Popliteal vein

6- Biceps femoris muscle

7- Semimembranosus muscle

8- Semitendinosus muscle

9- Soleus muscle

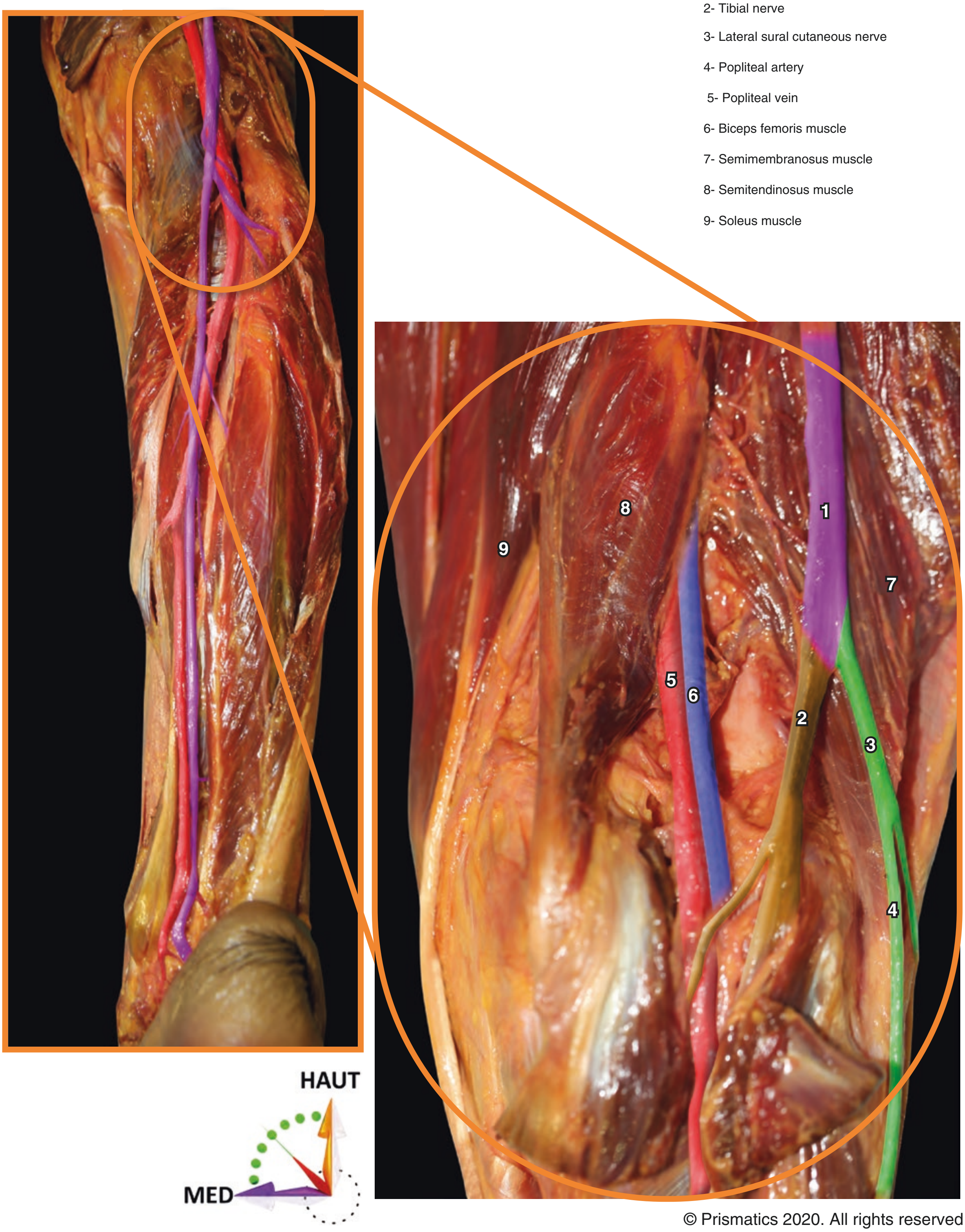


Figure T25. Surgical approach of the tibial nerve at the popliteal fossa level.

The Tibial Nerve

Surgical Indications

At the Ankle

Nerve damage at this level is rare. The most typical syndrome is represented by compression of the tibial nerve behind the medial malleolus under the medial annular ligament.

Skin Incision

The approach is curvilinear and goes around the malleolus, backwards to the inner surface of the foot (Figure T26). It is facilitated by interposition of a block under the opposite hip to facilitate external rotation of the leg.

Nervous Exposure

The flexor retinaculum of foot is incised to reveal the nerve. The latter is in depth of the tibialis posterior vessels, which have to be isolated and refined to access the nerve and its bifurcation into medial and lateral plantar nerve (Figure T26). It becomes more superficial when followed upwards, forward and inwards of the Achilles tendon.

N.B.: It is sometimes necessary to cut the abductor from the big toe to release the internal plantar bifurcation of the nerve downwards.

Technical Pitfalls

- Post-operative oedema of the limb in case of inadvertent coagulation of the adjacent venous network
- Vascular lesion of the popliteal axis at the leg and tibial arteries at the ankle

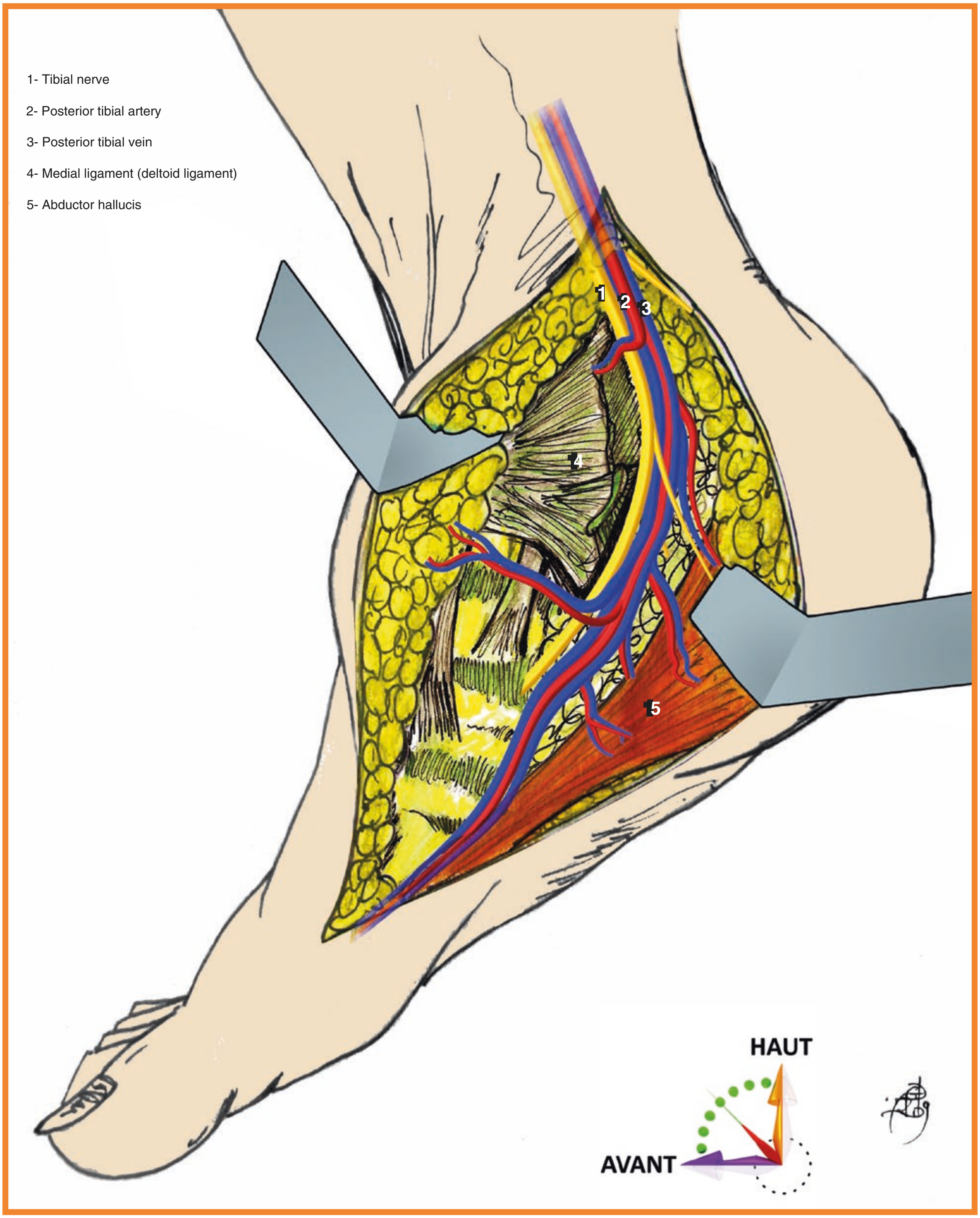
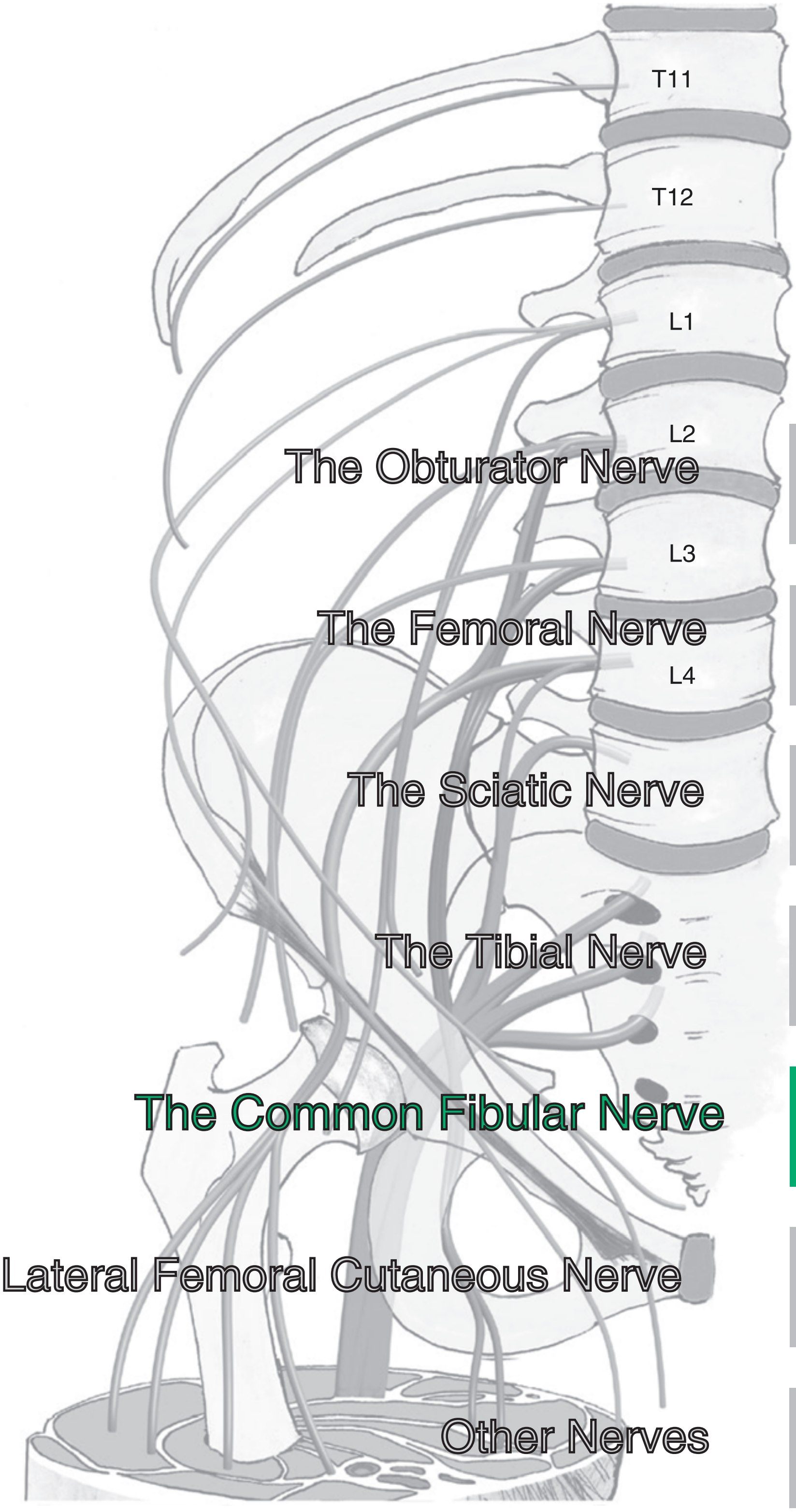

1- Tibial nerve
2- Posterior tibial artery
3- Posterior tibial vein
4- Medial ligament (deltoid ligament)
5- Abductor hallucis
1
2
3
4
5
HAUT
AVANT

Figure T26. Surgical approach of the tibial nerve at the ankle level.



The Obturator Nerve

The Femoral Nerve

The Sciatic Nerve

The Tibial Nerve

The Common Fibular Nerve

The Lateral Femoral Cutaneous Nerve

Other Nerves

The Fibular Nerve

Morphological Data

The common fibular nerve (also known as common peroneal nerve, peroneal nerve, external popliteal nerve, lateral popliteal nerve) is a mixed nerve and constitutes the lateral terminal branch of the sciatic nerve. It innervates the muscles of the anterolateral compartment of the leg and of the dorsal face of the foot, essentially through its terminal branches, the deep and superficial fibular nerves.

Origin

The common fibular nerve is made up of the L4, L5, S1 and S2 roots (Figures Fi1 and Fi2). It originates from the trunk of the sciatic nerve at the level of the popliteal fossa, in its uppermost vertex. At this point, it faces the tibial nerve medially, which is the medial and main terminal branch of the sciatic nerve.

Path

It goes downwards and laterally in the popliteal fossa. It then faces the tibial nerve medially and the upper part of the biceps femoris muscle laterally and then goes around its fibular insertion from below (Figure Fi3). It then passes above the proximal insertion of the lateral head of the gastrocnemius muscle, where it generally gives of the lateral sural cutaneous nerve (Figures Fi3, Fi8, Fi9, Fi10 and Fi11).

The fibular nerve then goes around the head of the fibula, between the tendon of the biceps femoris above and the lateral head of the gastrocnemius below (Figures Fi3 and 4Fi). It then goes through the crural intermuscular septum in order to place itself on the deep face of the peroneus longus muscle and to split into superficial fibular nerve and deep fibular nerve (Figure Fi5).

Neurovascular Relations

In the popliteal fossa, the common fibular nerve faces the popliteal vessels situated on the median axe of the limb medially (Figure T5, chapter "The Tibial Nerve").

In the leg, the superficial fibular nerve faces the perforating branch of the fibular artery laterally.

In the anterolateral face of the leg, the deep fibular nerve faces the anterior tibial artery medially and then laterally, which it crosses in front (Figures Fi4 and Fi6).

Collateral Branches

The fibular nerve gives off:

- A peroneal communicating nerve which makes an anastomosis with the medial sural cutaneous nerve, a branch of the tibial nerve
- The lateral sural cutaneous nerve, headed towards the skin
- A branch for the knee joint
- Branches for the tibialis anterior muscle, which originates slightly before the division of the fibular nerve

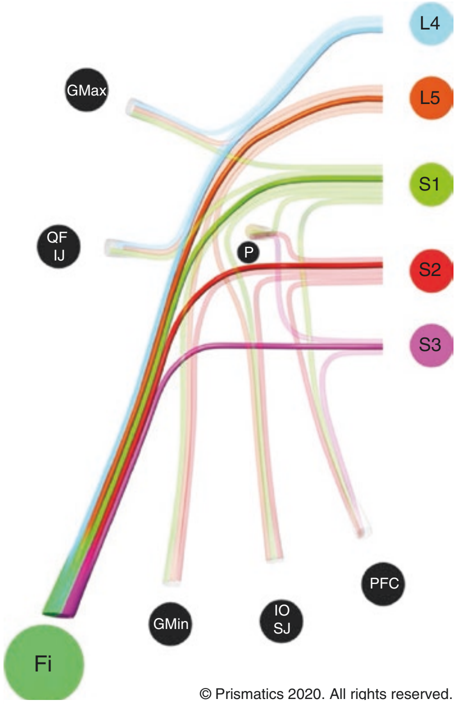
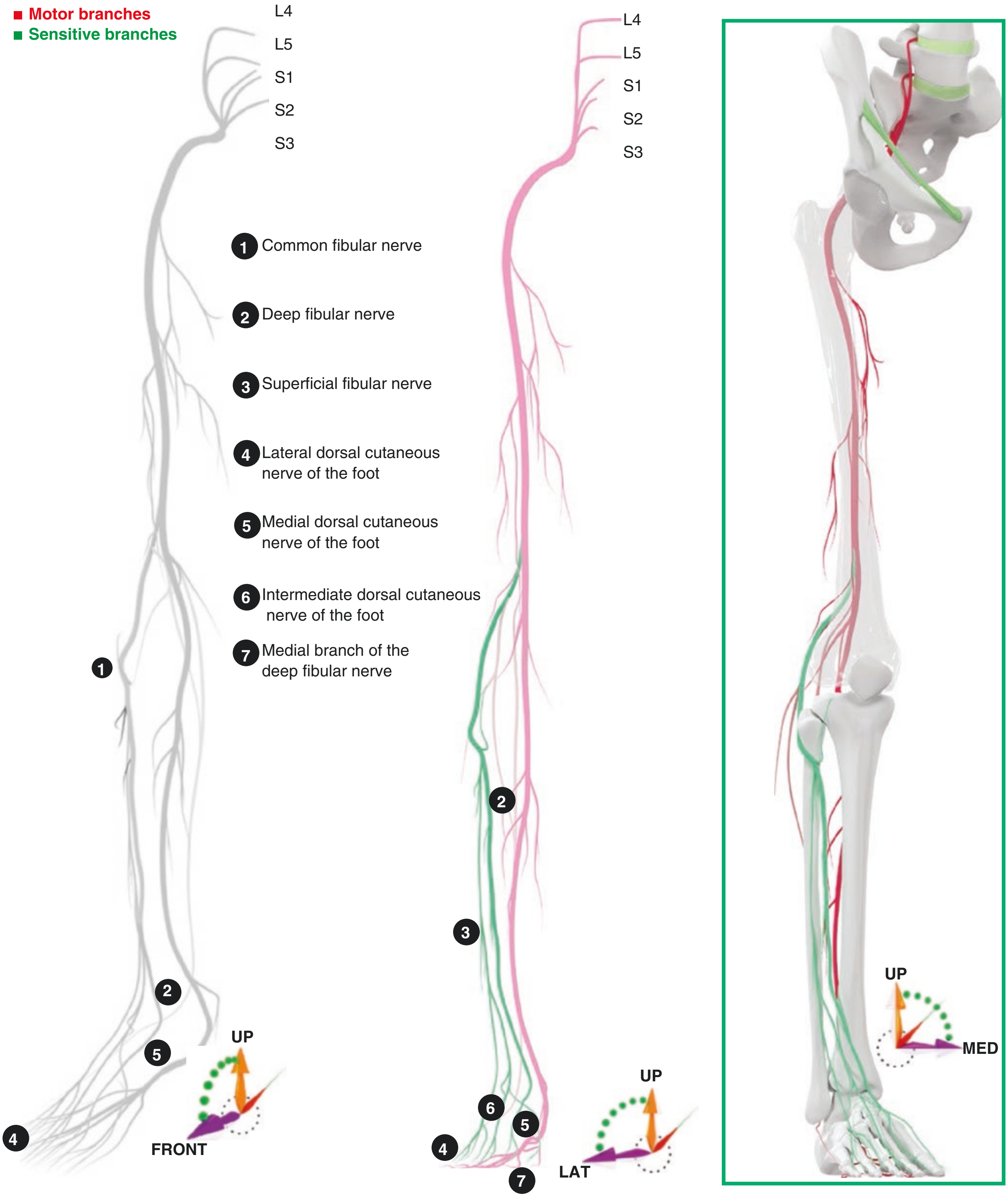


Figure Fi1. Origin of the fibular nerve.

Electronic Supplementary Material The online version of this chapter (https://doi.org/10.1007/978-3-030-49179-6_17) contains supplementary material, which is available to authorized users.


🟥 Motor branches
🟩 Sensitive branches
L4
L5
S1
S2
S3
1 Common fibular nerve
2 Deep fibular nerve
3 Superficial fibular nerve
4 Lateral dorsal cutaneous nerve of the foot
5 Medial dorsal cutaneous nerve of the foot
6 Intermediate dorsal cutaneous nerve of the foot
7 Medial branch of the deep fibular nerve
1
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5
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UP
FRONT
2
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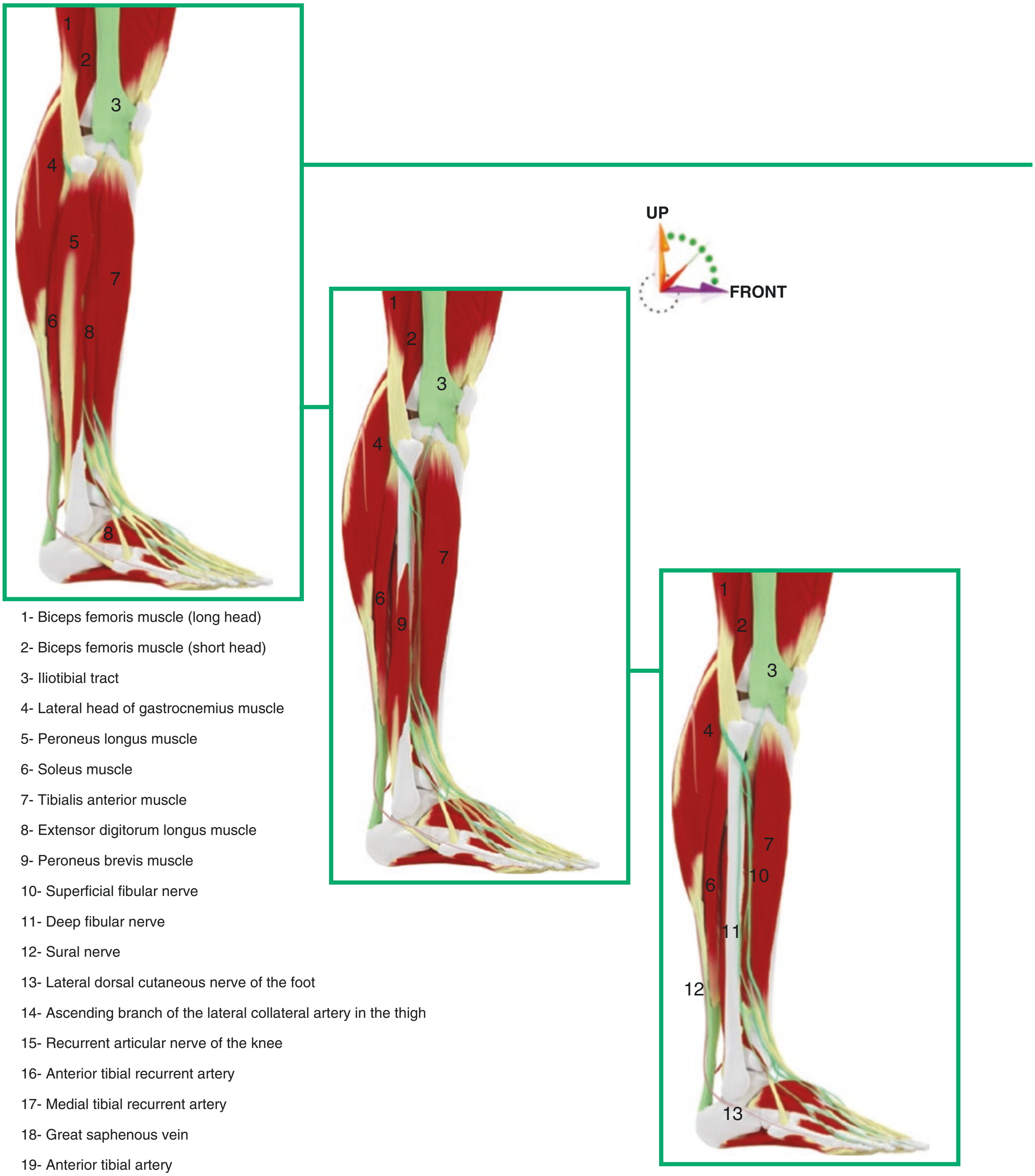
4
7
UP
LAT
UP
MED

Figure Fi2. Topographical distribution of the fibular nerve and its relations with bones.



1- Biceps femoris muscle (long head)
2- Biceps femoris muscle (short head)
3- Iliotibial tract
4- Lateral head of gastrocnemius muscle
5- Peroneus longus muscle
6- Soleus muscle
7- Tibialis anterior muscle
8- Extensor digitorum longus muscle
9- Peroneus brevis muscle
10- Superficial fibular nerve
11- Deep fibular nerve
12- Sural nerve
13- Lateral dorsal cutaneous nerve of the foot
14- Ascending branch of the lateral collateral artery in the thigh
15- Recurrent articular nerve of the knee
16- Anterior tibial recurrent artery
17- Medial tibial recurrent artery
18- Great saphenous vein
19- Anterior tibial artery

Figure Fi3. Muscular relations of the fibular nerve at the neck of the fibula and at the level of the anterior compartment of the leg (lateral view, from superficial to deep).

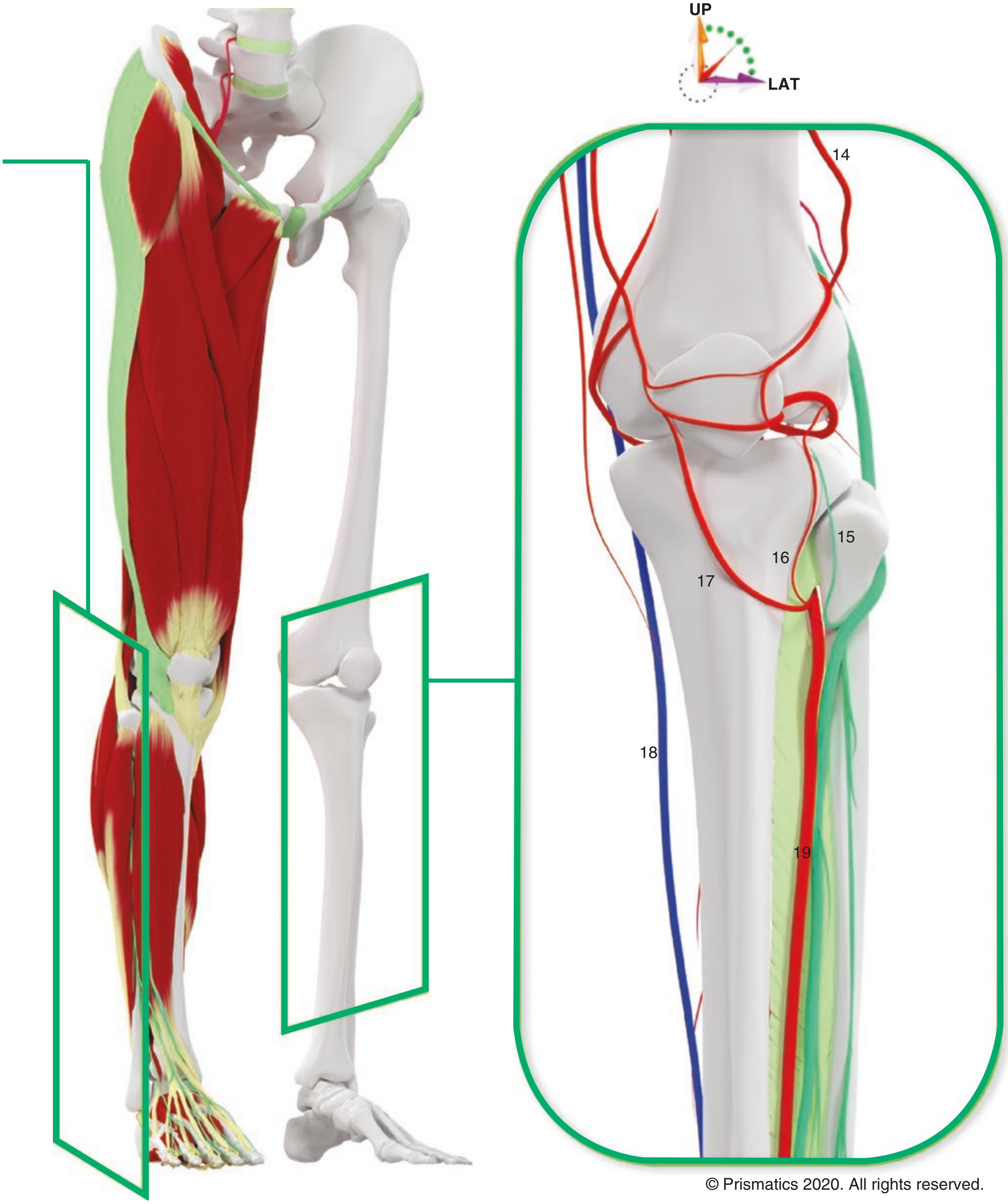

UP
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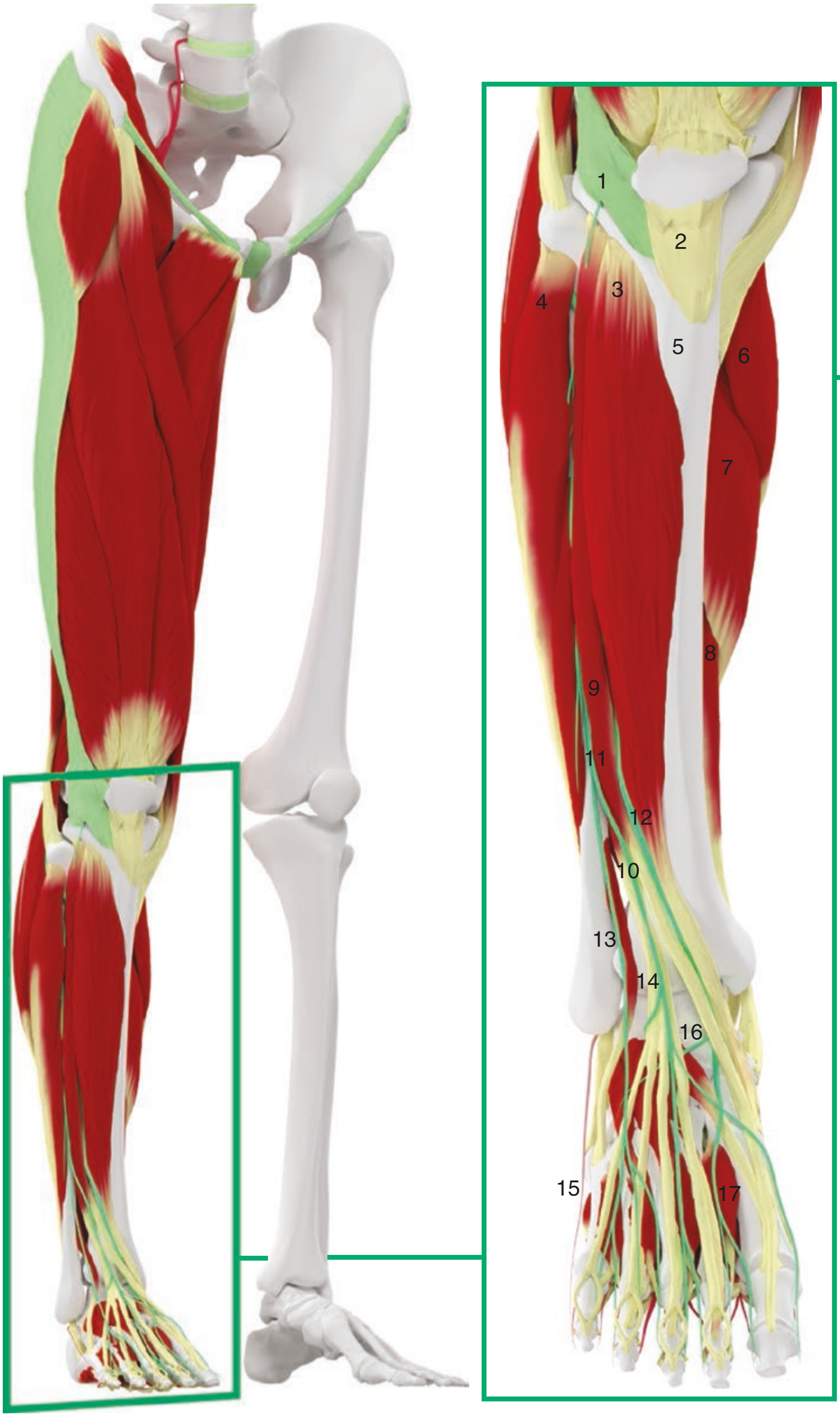
Figure Fi4. Neurovascular relations of the fibular nerve at the neck of the fibula and at the level of the anterior compartment of the leg (anterior view).



1- Iliotibial tract
2- Patellar ligament
3- Tibialis anterior muscle
4- Peroneus longus muscle
5- Tibia
6- Medial head of gastrocnemius muscle
7- Soleus muscle
8- Flexor digitorum longus muscle
9- Extensor hallucis longus muscle
10- Extensor digitorum longus muscle
11- Superficial fibular nerve
12- Deep fibular nerve
13- Intermediate dorsal cutaneous nerve
14- Medial dorsal cutaneous nerve
15- Lateral dorsal cutaneous nerve
16- Lateral branch of the deep fibular nerve
17- Medial branch of the deep fibular nerve

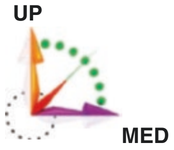
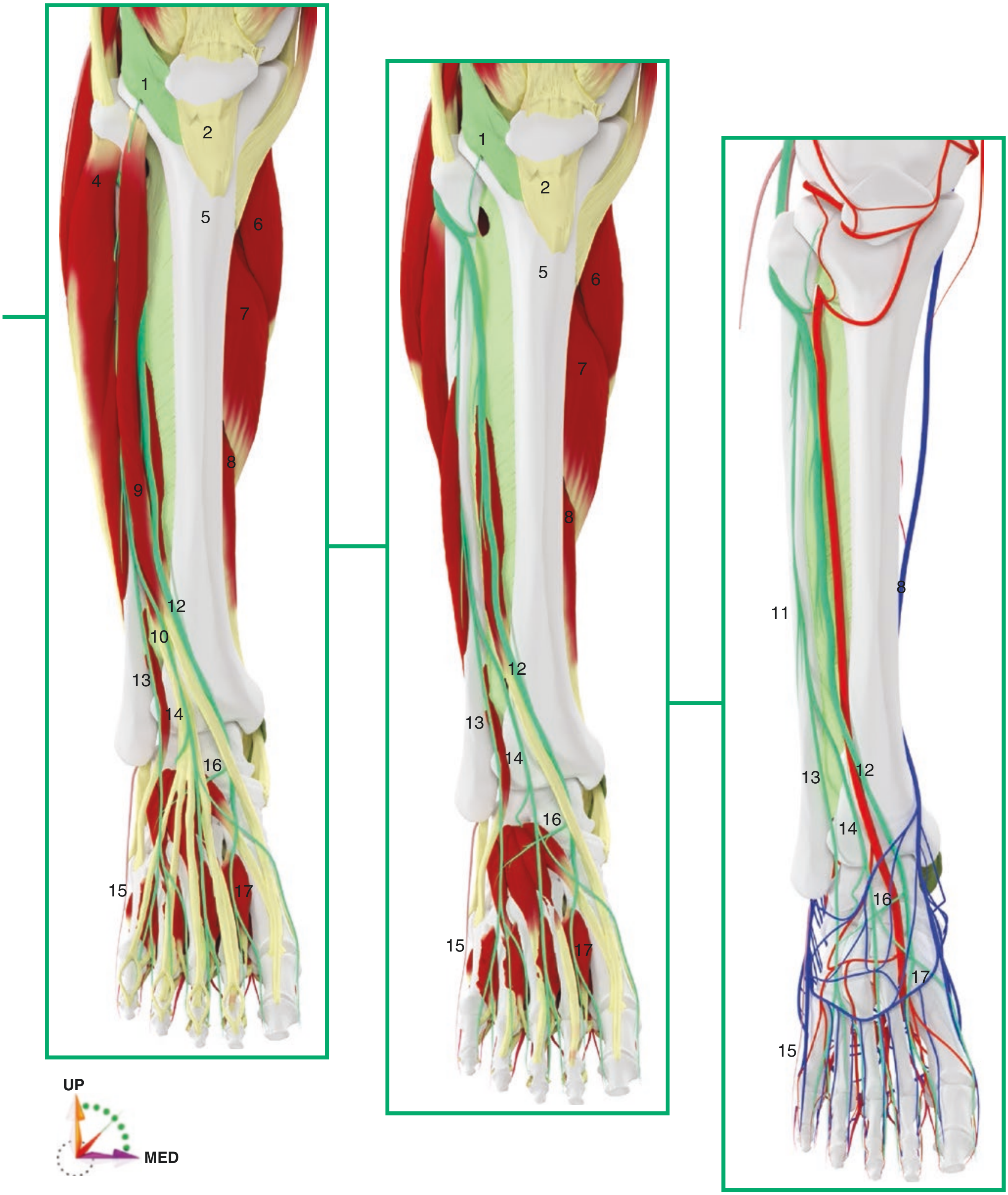


Figure Fi5. Muscular relations of the fibular nerve in the leg.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UP
MED

Figure Fi6. Neurovascular and muscular relations of the fibular nerve in the leg.

The Fibular Nerve

Terminal Branches

The fibular nerve divides into two terminal branches between the two insertions of the peroneus longus muscle. It gives off the superficial fibular nerve, which is lateral, and the deep fibular nerve, which is medial (Figure Fi2).

The superficial fibular nerve (formerly known as the musculocutaneous nerve of the leg) makes its way along the deep face of the peroneus longus muscle and then between the peroneus longus and brevis laterally and extensor digitorum longus medially. It perforates the anterior intermuscular aponeurosis at the inferior third of the leg and gives off several branches, which are headed towards the skin. On its path, the superficial fibular nerve gives off several collateral branches: muscular branches for the peroneus longus and brevis muscles and then cutaneous branches, notably for the lateral malleolus (Figure Fi5).

The superficial fibular nerve then splits into two terminal branches, in front of the extensor retinaculum (Figure Fi6):

- The medial branch gives off the medial dorsal digital nerve of the hallux and a branch that is headed towards the first interosseous space and splits into two dorsal collateral digital nerves: lateral of the hallux and medial of the second toe. It also gives off a third branch for the second interosseous space, which splits into two dorsal digital nerves—lateral of the second toe and medial of the third toe.
- The lateral branch follows the same path and gives off the branches of the third and fourth interosseous spaces. It therefore gives off several dorsal digital nerves: lateral of the third toe, medial of the fourth toe, lateral of the fourth toe and medial of the fifth toe.

The deep fibular nerve (formerly known as the anterior tibial nerve) also originates between the two insertions of the peroneus longus muscle. It goes around the neck of the fibula, then makes its way on the deep face of the extensor digitorum longus and joins the anterior tibial artery slightly in front of the interosseous membrane, at the upper third of the leg (Figure Fi4). With this membrane, it forms the anterior neurovascular bundle until the ankle, where it divides into lateral and medial terminal branches. On the anterior face of the leg, the deep fibular nerve faces the anterior tibial artery medially and the extensor digitorum longus laterally (Figure Fi6). In front, the tibialis anterior muscle can be found medially, and the extensor digitorum longus can be found laterally. In the lower part of the leg, the extensor hallucis longus, which was lateral, comes over the neurovascular pedicle and covers it.

The deep fibular nerve gives off several collateral branches:

- Muscular branches for the tibialis anterior, extensor digitorum longus, extensor hallucis longus and peroneus longus and brevis (Figure Fi7).
- Articular branches for the tibial–tarsal joint.
- It ends after going under the extensor retinaculum, forming two branches: lateral and medial.

The medial branch extends the path of the dorsal artery of the foot (also known as dorsalis pedis artery) whilst remaining lateral in relation to this artery until the first interosseous space. It then divides to support or replace the lateral dorsal digital nerve of the hallux and medial dorsal digital nerve of the second toe. The cutaneous innervation of these toes by these branches remains inconstant.

The lateral branch goes under the dorsal tarsal artery and under the extensor hallucis brevis muscle, which it innervates, as well as the extensor hallucis muscle (Figure Fi6).

Motor Function

The fibular nerve innervates the muscles of the anterolateral compartment of the leg (Figure Fi7): tibialis anterior, extensor digitorum longus, extensor hallucis longus and peroneus longus and brevis. It also innervates the muscles of the dorsal face of the foot—extensor digitorum brevis and extensor hallucis brevis.

It is therefore in charge of the flexion of the foot on the leg, the eversion of the foot and extension of the toes.

Sensitive Function

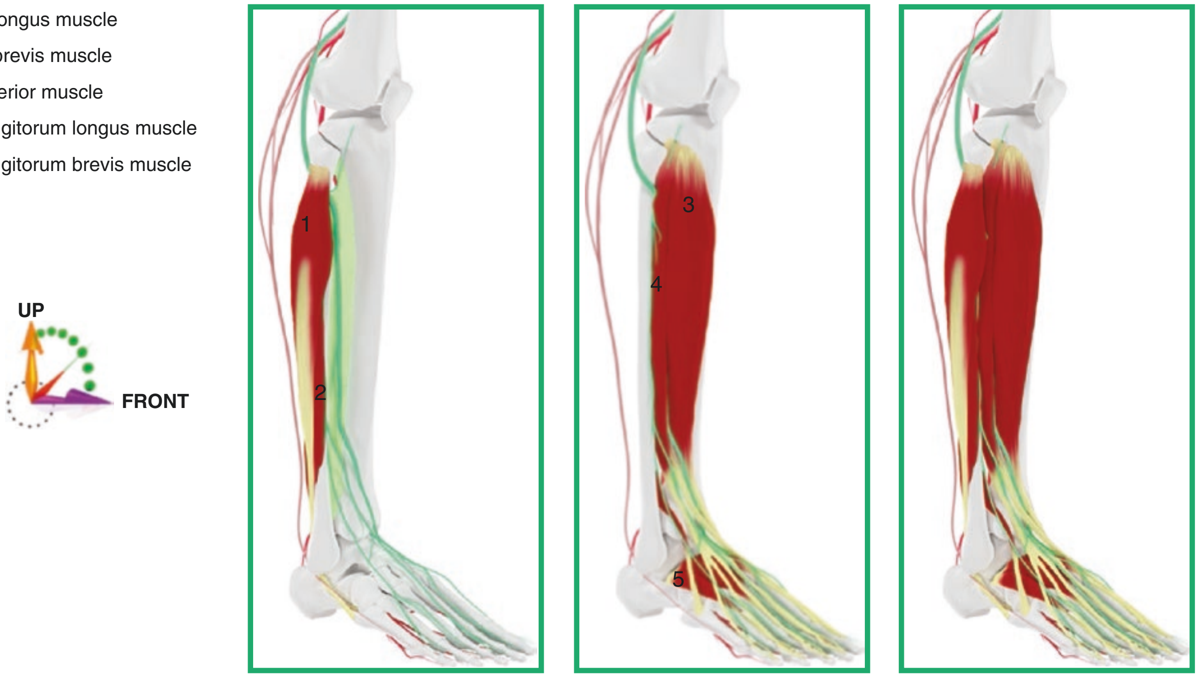
The sensitive function of the fibular nerve mainly originates from the superficial fibular nerve (Figures Fi7, Fi8, Fi9, Fi10 and 11). Its territory concerns the dorsal face of the foot, under the territories of the saphenous and lateral sural cutaneous nerves and medially in relation to the territory of the sural nerve. The medial distal branch of the deep fibular nerve takes charge of the innervation of the first interdigital space.

Anastomoses

The fibular nerve can make anastomoses, either directly or through its terminal branches, with:

- The tibial nerve
- The sural nerve through the peroneal communicating nerve (this anastomosis is almost constant)
- The saphenous nerve
- The lateral femoral cutaneous nerve

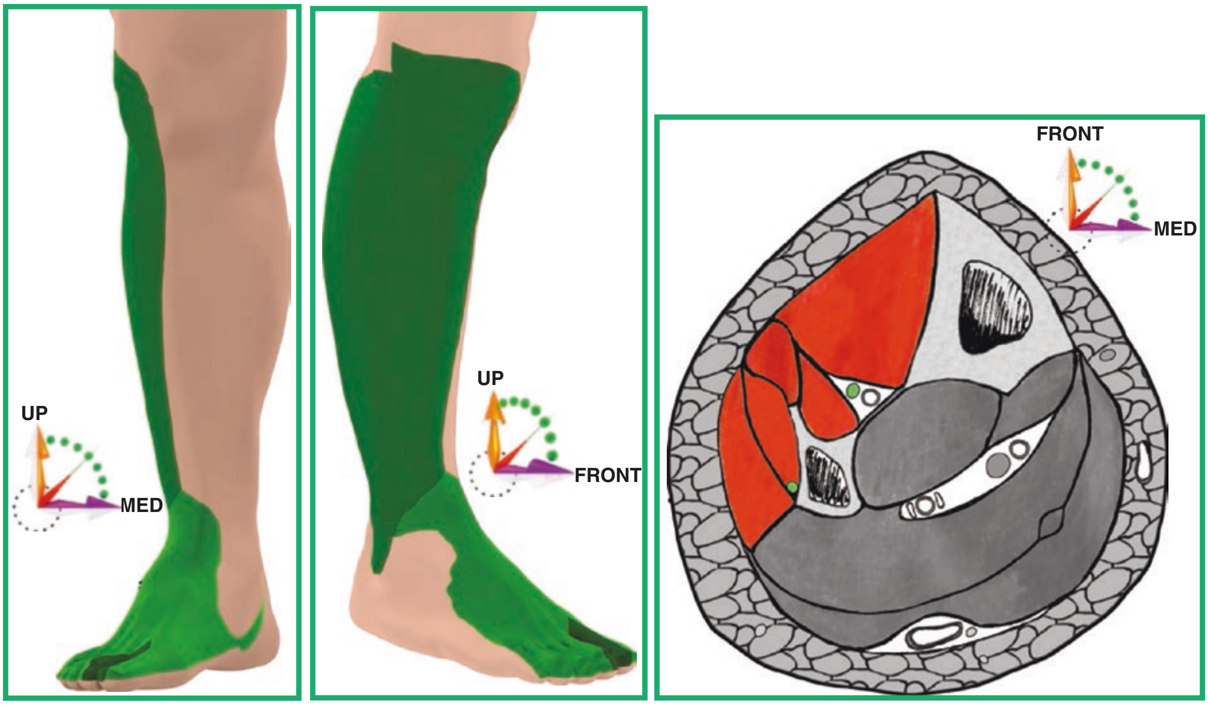
1- Peroneus longus muscle
2- Peroneus brevis muscle
3- Tibialis anterior muscle
4- Extensor digitorum longus muscle
5- Extensor digitorum brevis muscle



Motor innervation of the superficial branch

Motor innervation of the deep branch

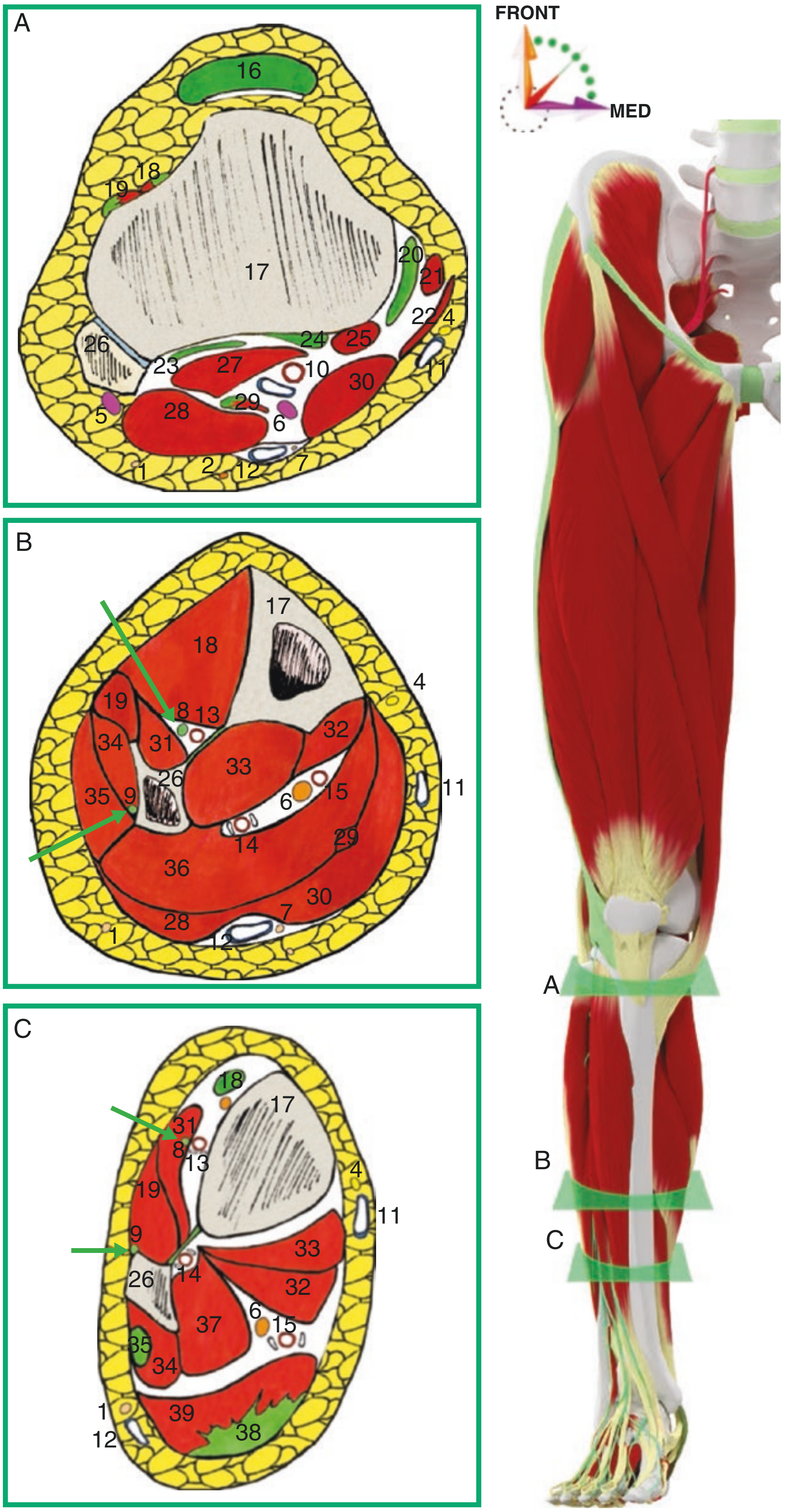
Motor innervation of the fibular nerve



🟩 Lateral sural cutaneous nerve
🟩 Superficial fibular nerve
🟩 Deep fibular nerve

Figure Fi7. Motor and sensitive innervation of the fibular nerve.

1- Lateral sural cutaneous nerve
2- Peroneal communicating nerve
3- Medial sural cutaneous nerve
4- Saphenous nerve
5- Fibular nerve
6- Tibial nerve
7- Sural nerve
8- Deep fibular nerve
9- Superficial fibular nerve
10- Popliteal artery and vein
11- Great saphenous vein
12- Small saphenous vein
13- Anterior tibial artery
14- Fibular artery and vein
15- Posterior tibial artery
16- Patellar ligament of quadriceps femoris muscle
17- Tibia
18- Tibialis anterior muscle
19- Extensor digitorum longus muscle
20- Medial collateral ligament
21- Gracilis muscle
22- Sartorius muscle
23- Synovial bursa
24- Posterior cruciate ligament
25- Semimembranosus muscle
26- Fibula
27- Popliteus muscle
28- Lateral head of the gastrocnemius muscle
29- Plantaris muscle
30- Medial head of the gastrocnemius muscle
31- Extensor hallucis longus muscle
32- Flexor digitorum longus muscle
33- Posterior tibial muscle
34- Peroneus brevis muscle
35- Peroneus longus muscle
36- Soleus muscle
37- Flexor hallucis longus muscle
38- Calcaneal tendon
39- Triceps surae muscle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31
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33
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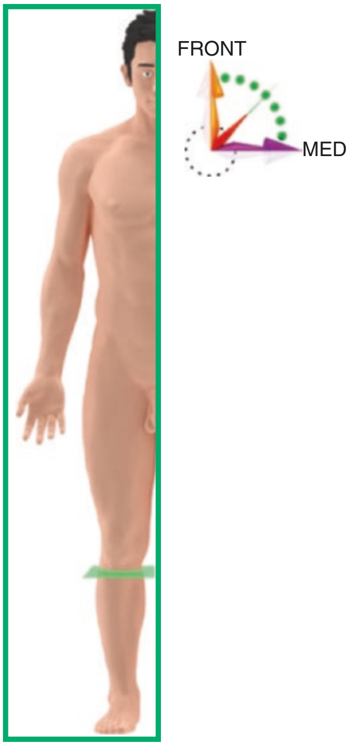
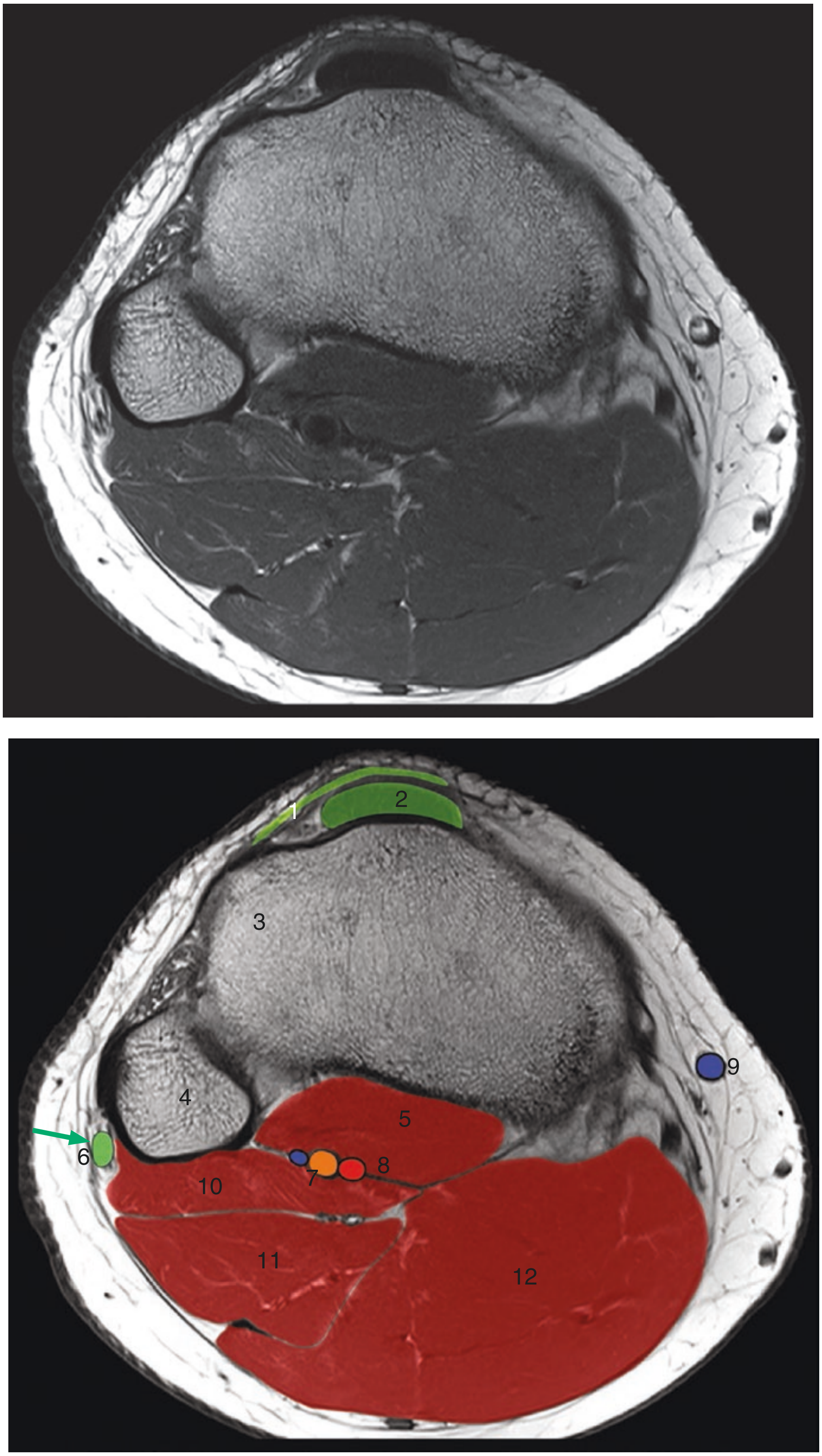
B
C

Figure Fi8. Relations of the fibular nerve in the leg, axial sections.





1- Patellar ligament
2- Deep infrapatellar bursa
3- Tibia
4- Fibula
5- Popliteus muscle
6- Common fibular nerve
7- Posterior tibial artery and vein
8- Tibial nerve
9- Great saphenous vein
10- Soleus muscle
11- Lateral head of gastrocnemius muscle
12- Medial head of gastrocnemius muscle

Figure Fi9. MRI scans at the proximal third of the leg through the fibular nerve.

1- Extensor digitorum longus muscle

2- Tibialis anterior muscle

3- Tibia

4- Flexor digitorum longus muscle

5- Deep fibular nerve

6- Anterior tibial artery and vein

7- Great saphenous vein

8- Peroneus longus and brevis muscles

9- Fibula

10- Posterior tibial muscle

11- Posterior tibial artery and vein

12- Tibial nerve

13- Flexor hallucis longus muscle

14- Lateral head of gastrocnemius muscle

15- Medial head of gastrocnemius muscle

16- Small saphenous vein

17- Medial sural cutaneous nerve

18- Sural nerve

19- Soleus muscle

20- Extensor hallucis longus muscle

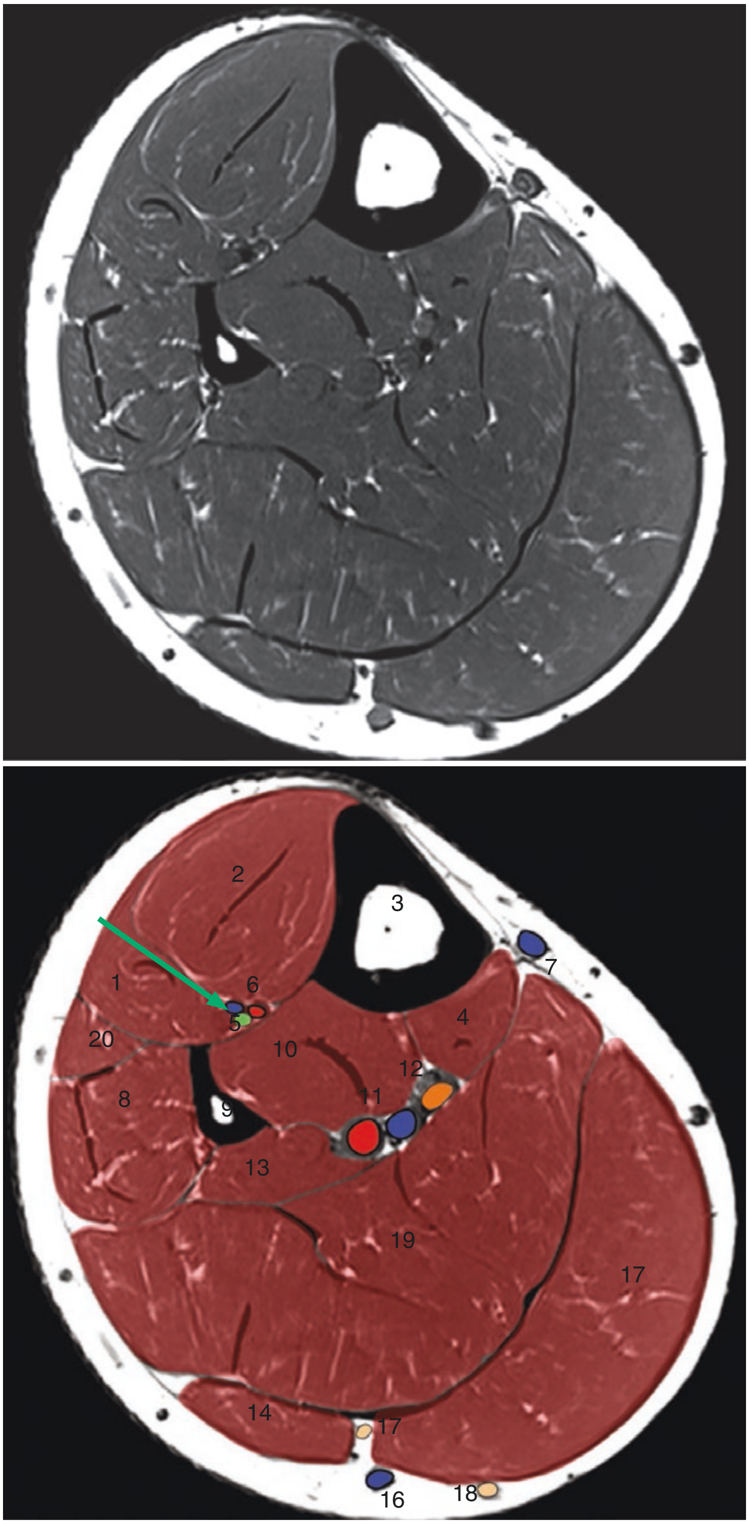
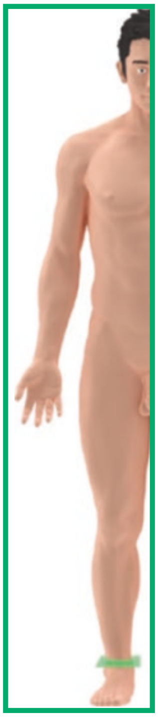
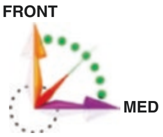
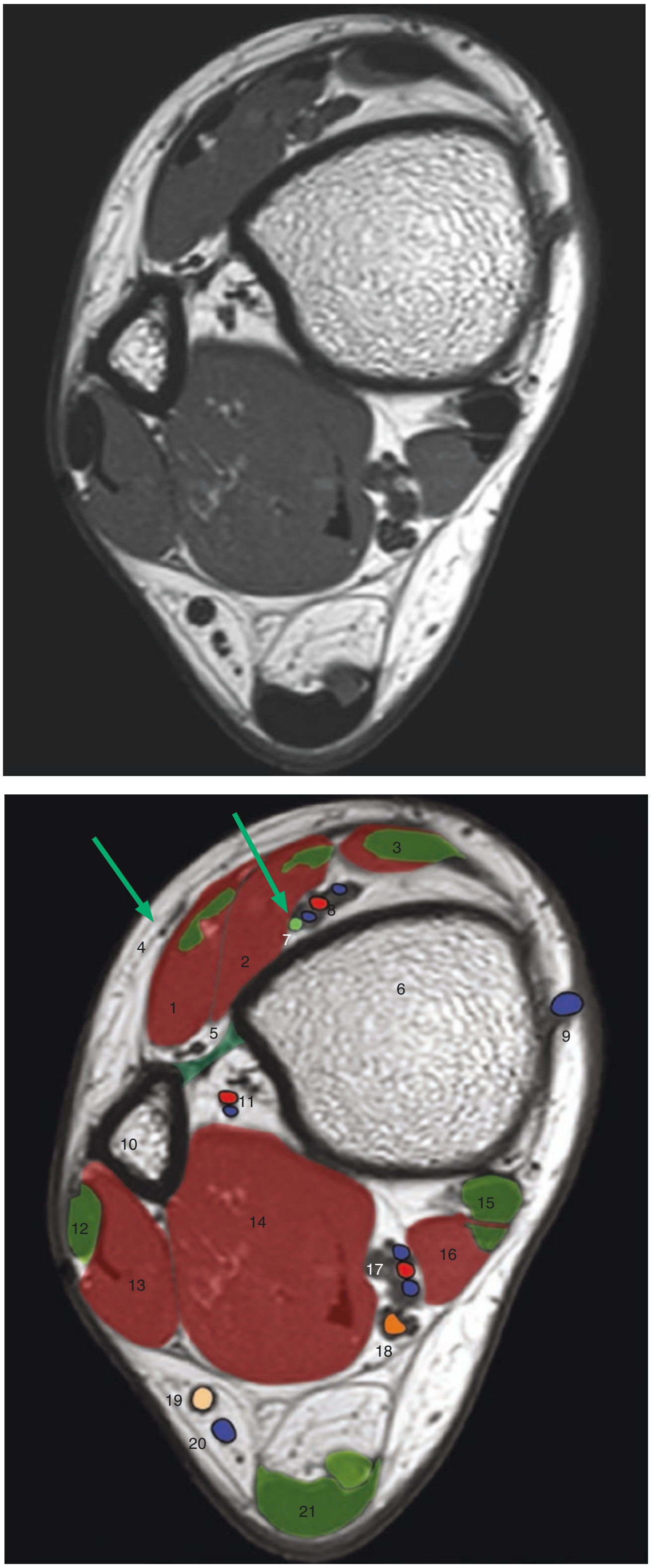


Figure Fi10. MRI scans at the distal third of the leg through the fibular nerve.







1- Extensor digitorum longus muscle
2- Extensor hallucis longus muscle
3- Tendon of the tibialis anterior muscle
4- Superficial fibular nerve
5- Interosseous membrane
6- Tibia
7- Deep fibular nerve
8- Anterior tibial artery and vein
9- Great saphenous vein
10- Fibula
11- Fibular artery and vein
12- Tendon of the peroneus longus muscle
13- Peroneus brevis muscle
14- Flexor hallucis longus muscle
15- Tendon of the posterior tibial muscle
16- Flexor digitorum longus muscle
17- Posterior tibial artery and vein
18- Tibial nerve
19- Sural nerve
20- Small saphenous vein
21- Tendons of the triceps surae and plantaris muscles

Figure Fi11. MRI scans in the ankle through the fibular nerve.

Pathology

Fibular Nerve Injury

The fibular nerve is a mixed nerve originating from the sciatic nerve. It originates in the popliteal fossa and goes around the neck of the fibula in order to innervate the muscles of the anterolateral compartment of the leg.

Aetiology

In most cases, various mechanisms can be found:

- Compression: A compression generally occurs at the level of the neck of the fibula, which is a sensible area of the common fibular nerve. This compression can be postural, perioperative, caused by a quick loss of weight, prolonged bed rest or an orthopaedic splint. A compression also may or may not occur from cancer lesions in variable proportions according to studies.
- Section: Knee injuries are commonly implied.
- Traction: This mechanism favours positional injuries, which generally occur when the knee is flexing.
- Ischaemia: Knee injuries can affect the popliteal artery, which cause poor functional prognosis ischaemia for the common fibular nerve.

Clinical Significance

- Sensitive signs: The pain on the antero-external face of the leg can evoke a paramedial L4–L5 discal herniation or a foraminal L5–S1 discal herniation, but the topography of the sensitive signs is slightly different. These can be elicited by using Tinel's sign at the level of the neck of the fibula. Hypoesthesia can be found on the dorsal side of the foot.
- Motor signs: The common fibular nerve takes charge of the motor innervation of the tibialis anterior, extensor hallucis longus, extensor digitorum longus and peroneus longus and brevis muscles. As such, an injury of this nerve causes a foot drop gait caused by a dysfunction in the flexion of the foot on the leg. A decrease of the ability of eversion of the foot can also be noticed, as this eversion is mainly performed by the peroneus muscles.

Clinical Forms

A classic form of injury, known as the "grape-picker palsy", may happen in a professional context. It is an entrapment neuropathy in which the common fibular nerve gets compressed at the level of the neck of the fibula.

If there is no notion of trauma in the patient's history, there may however be some relevant sports activities: running or intensive jogging, favoured positions or particular habits.

Explorations

- An electroneuromyography can show a slowdown or a conduction block on the path of the nerve at the level of the neck of the fibula.
- If there is no traumatic context, an imagery of the knee makes research of a tumour possible. If there is a trauma, most notably leg torsion or malleolar fracture, a few simple radiographies will help in looking for a proximal fibular fracture in cases of Maisonneuve fractures (associated medial malleolus injury, mimicking a bimalleolar fracture).

Treatment

Immediate surgery is only recommended in cases of extrinsic compression which must be relieved quickly if the dysfunctions are sudden or recent or tend to evolve.

Different types of surgery can be suggested if there is no post-traumatic recovery or entrapment neuropathies. These surgeries consist of releasing the nerve at the level of the neck of the fibula (Figure Fi12).

In cases of "medical" causes, a surgery must only be envisioned as a secondary option, after failure of a well-conducted medical treatment.

In published series, this surgery bears interesting results in all cases, with minimal invasion.

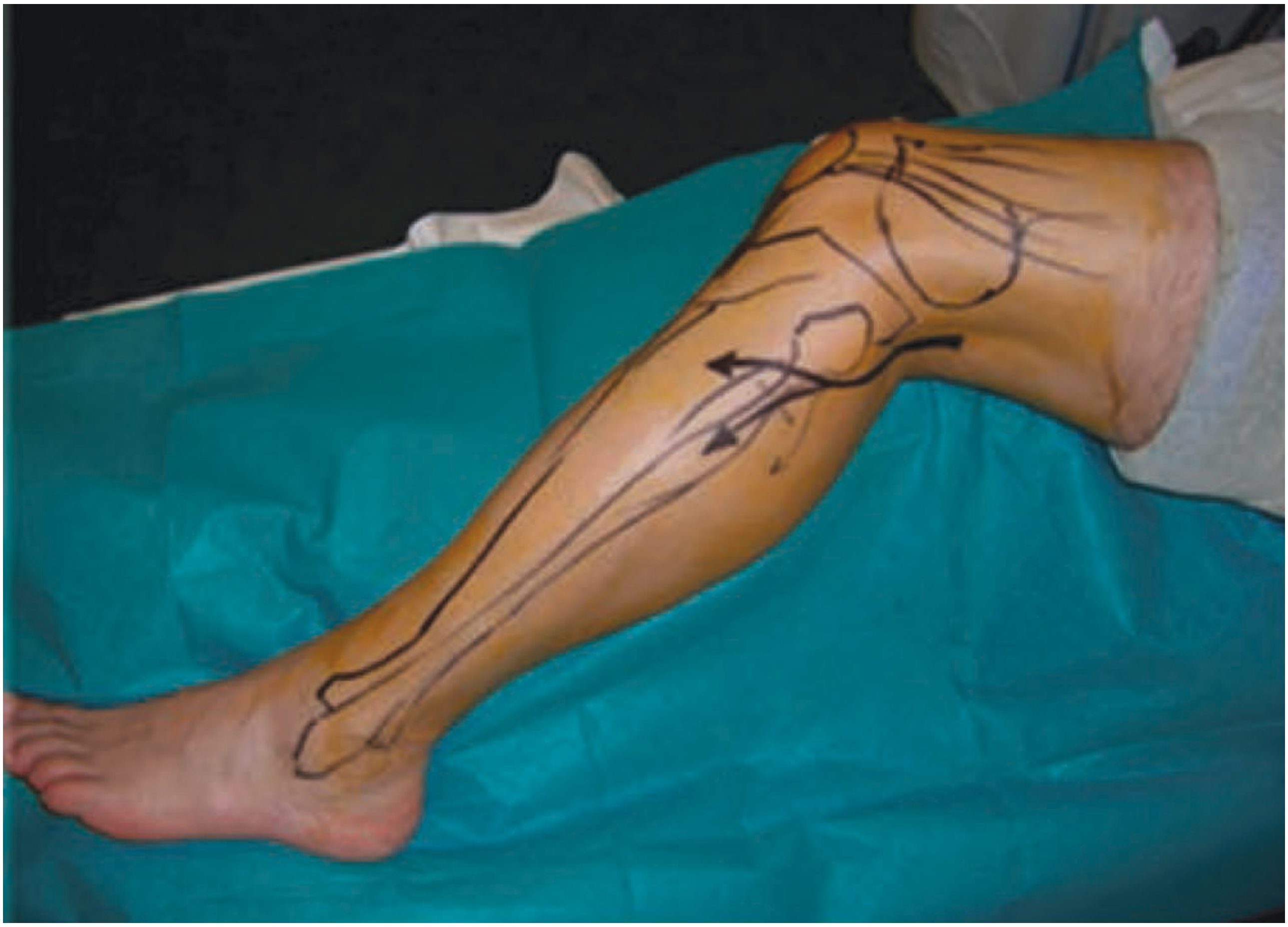


Figure Fi12. Entrapment of the fibular nerve at the neck of the fibula.

Morphological Data: Sono Anatomy

Installation

The patient can be installed:

- In lateral decubitus, lying on the side not concerned by the ultrasound procedure, the knee slightly bent to relax the triceps surae muscle and the foot in support.
- In supine position, knee bent, lifted off the plane of the intervention table to allow the sonographer to access this area. The foot will be resting on the heel.

Equipment and Location

- Probe type: linear, high frequency
- Probe axis: initially transverse and then longitudinal after ultrasound scanning

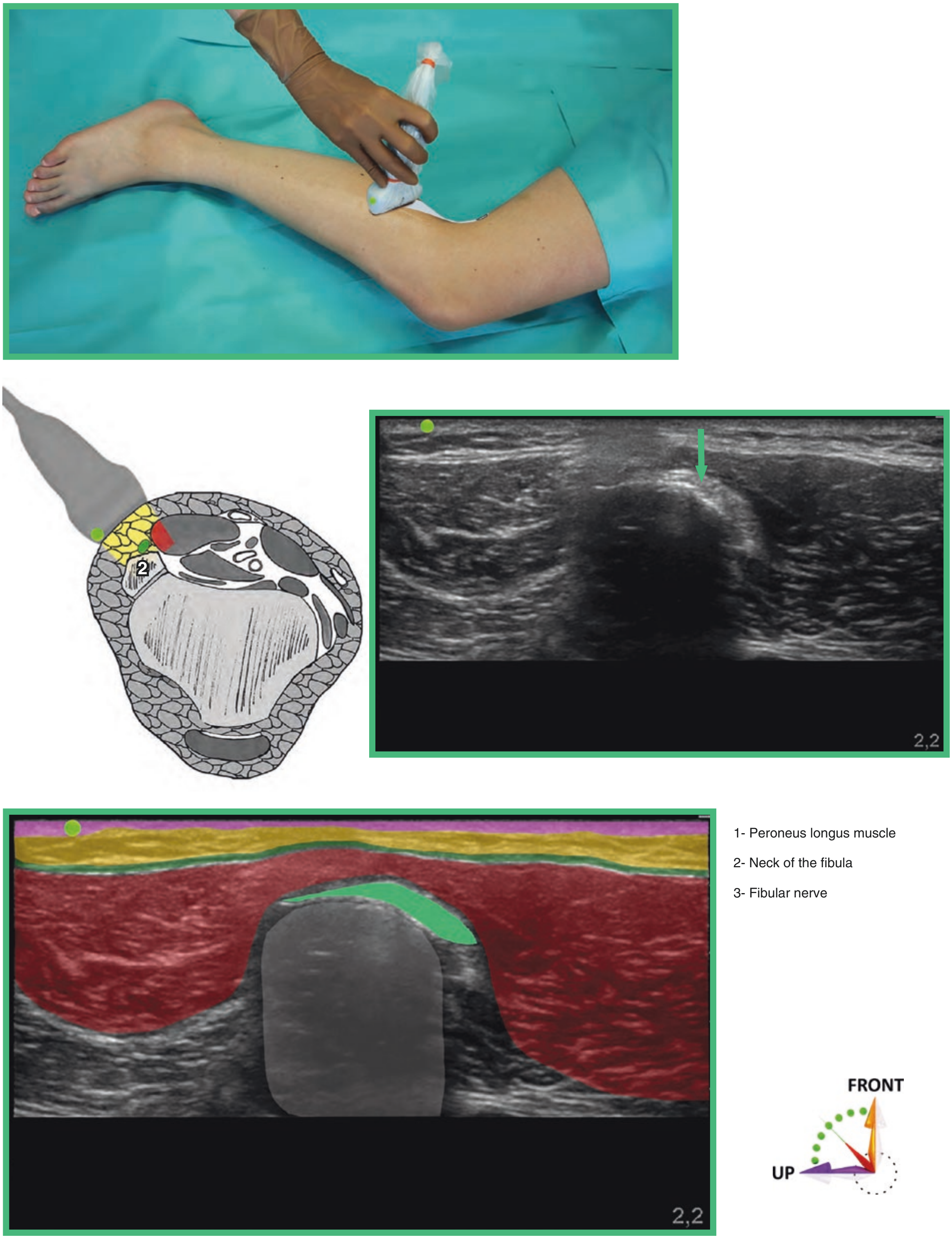
Ultrasound Procedure

Identification of the Common Fibular Nerve in the Cervix

The aim is to position the probe permanently in the longitudinal axis of the nerve, especially when it passes through the fibula neck.

To do this, the probe will follow a spiral movement to wind itself, exactly like the nerve, from a region where it is almost median and posterior to a region where it is more anterior and lateral. The idea is to ideally follow the path of the common fibular nerve from the popliteal region to the fibula neck, positioning the probe in the axial cut position at the biceps femoris muscle and then gradually bending it, whilst remaining in strict axial cut, entering the longitudinal axis of the nerve opposite the fibula neck, thanks to this twisting movement. At this stage of identification, a forward and forward curve of the probe will allow the operator to move from a strictly axial to an oblique plane, so that the nerve is optimally visible longitudinally, despite its bony environment. This nerve can be "rolled" by this precise movement, rotating it back and forth.

It will then divide into superficial fibular nerve and deep fibular nerve, the latter drawing our attention (Figures Fi13 and Fi14).



1- Peroneus longus muscle
2- Neck of the fibula
3- Fibular nerve

Figure Fi13. Ultrasound transversal views of the fibular nerve at the neck of the fibula.

The Fibular Nerve

Deep Fibular Nerve

Installation

Supine position, leg in slight internal rotation, slight plantar flexion or knee bent, foot flat.

Equipment and Location

- Type of probe: superficial, straight
- Probe axis: sagittal between lateral and medial malleoli, axial cut of the nerve
- Parameter setting: low depth

The deep fibular nerve punctures the spans of the extensor digitorum longus muscle and travels next to the tibialis anterior artery.

Ultrasound Procedure

The deep fibular nerve is lateral to the tibialis anterior artery in 90% of cases, but there are many anatomical variations. In 22% of cases, an accessory deep fibular nerve travels behind the lateral malleolus and innerves the extensor digitorum brevis muscle outside the tarsal tunnel.

At the lower one third of the leg, the deep fibular nerve passes behind the extensor hallucis longus muscle.

Its location begins about 3 cm above the ankle joint. It travels at this level between extensor hallucis longus and extensor digitorum longus muscles.

In general, the division into medial and lateral branches is done downstream of the lower retinaculum of the extensors, but there are many anatomical variations.

Given the narrowness of the tunnel and the proximity of the vessels, the compression/decompression technique is used to identify venous structures and colour Doppler for arterial structures (Figures Fi15–Fi18).

Superficial Fibular Nerve

The superficial fibular nerve originates from the lateral branch of the lateral bifurcation of the common fibular nerve, along the lateral surface of the fibula, and descends between the lateral muscles (peroneus longus) and the anterior intermuscular septum. At the lower one third of the leg, it punctures the fascia and becomes subcutaneous in the lateral compartment.

Installation

Patient in supine position and plantar flexion or knee bent.

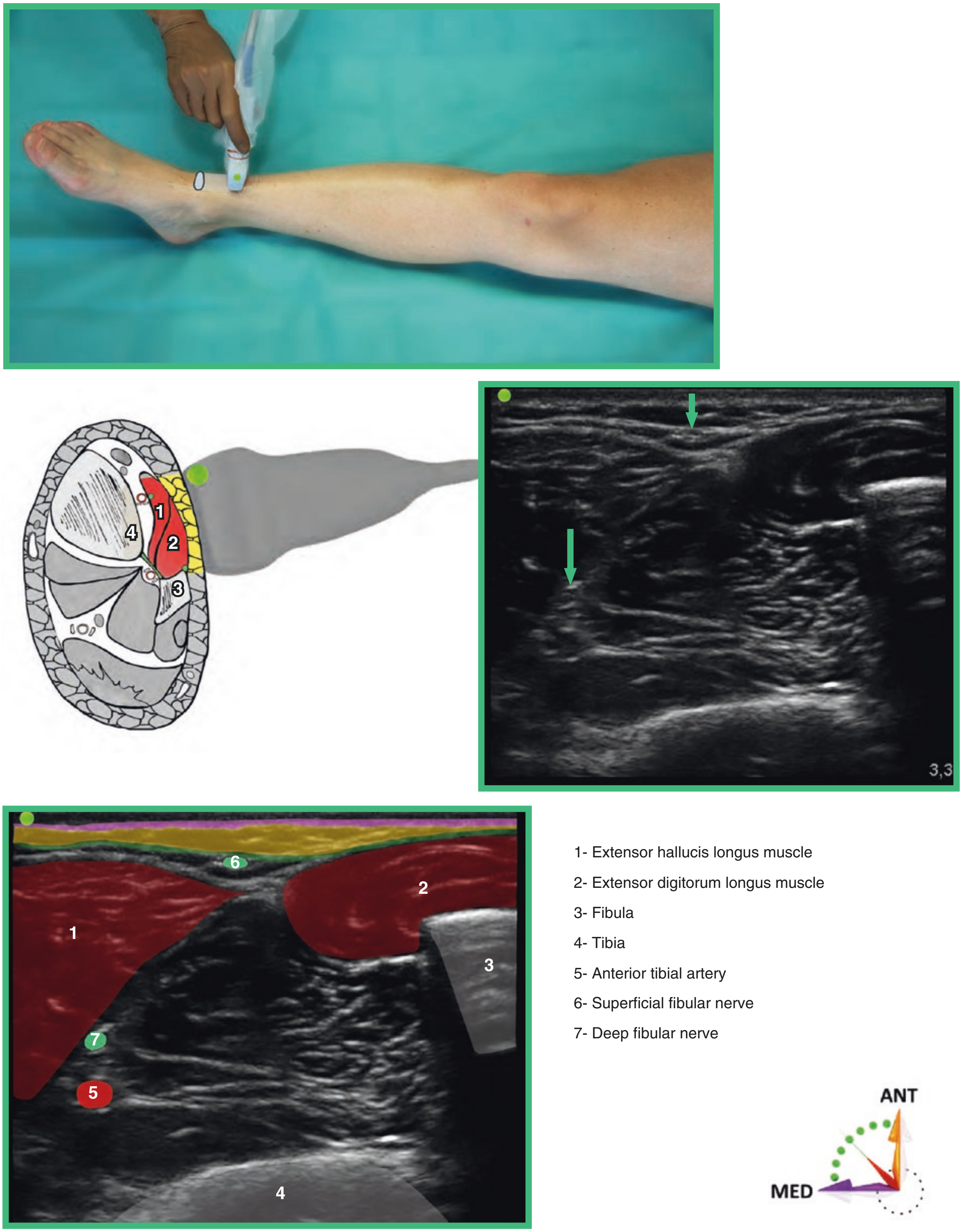
Equipment and Location

- Type of probe: superficial, high frequency, if possible in the shape of a stick

Ultrasound Procedure

The probe is positioned axially, and the locating will be done as is the case for the deep branch of the fibular nerve, insofar as it rotates at the junction of the middle and distal third of the leg, arriving at the dorsal surface of the instep, thereby ensuring sensitive innervation of this region.

To our knowledge, there is no specific intervention procedure for this branch of the fibular nerve (Figure Fi19).



1- Extensor hallucis longus muscle
2- Extensor digitorum longus muscle
3- Fibula
4- Tibia
5- Anterior tibial artery
6- Superficial fibular nerve
7- Deep fibular nerve

Figure Fi14. Ultrasound transversal views of the superficial and deep branches of the fibular nerve at the distal third of the leg.

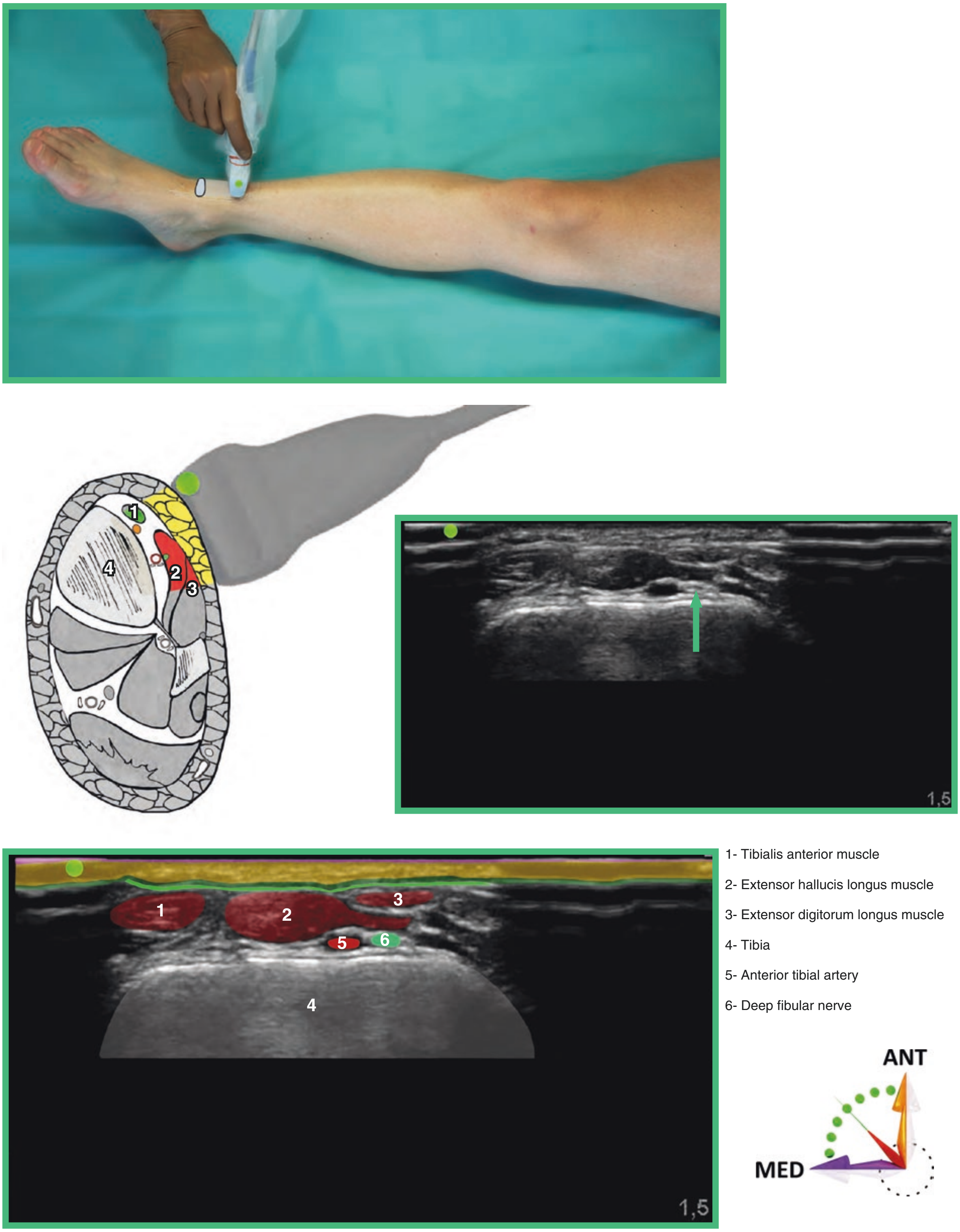

1
4
2
3
1,5
1
2
3
5
6
4
1,5
1- Tibialis anterior muscle
2- Extensor hallucis longus muscle
3- Extensor digitorum longus muscle
4- Tibia
5- Anterior tibial artery
6- Deep fibular nerve
ANT
MED

Figure Fi15. Ultrasound transversal views of the deep fibular nerve (3 cm above the ankle, at the extensor retinaculum level).

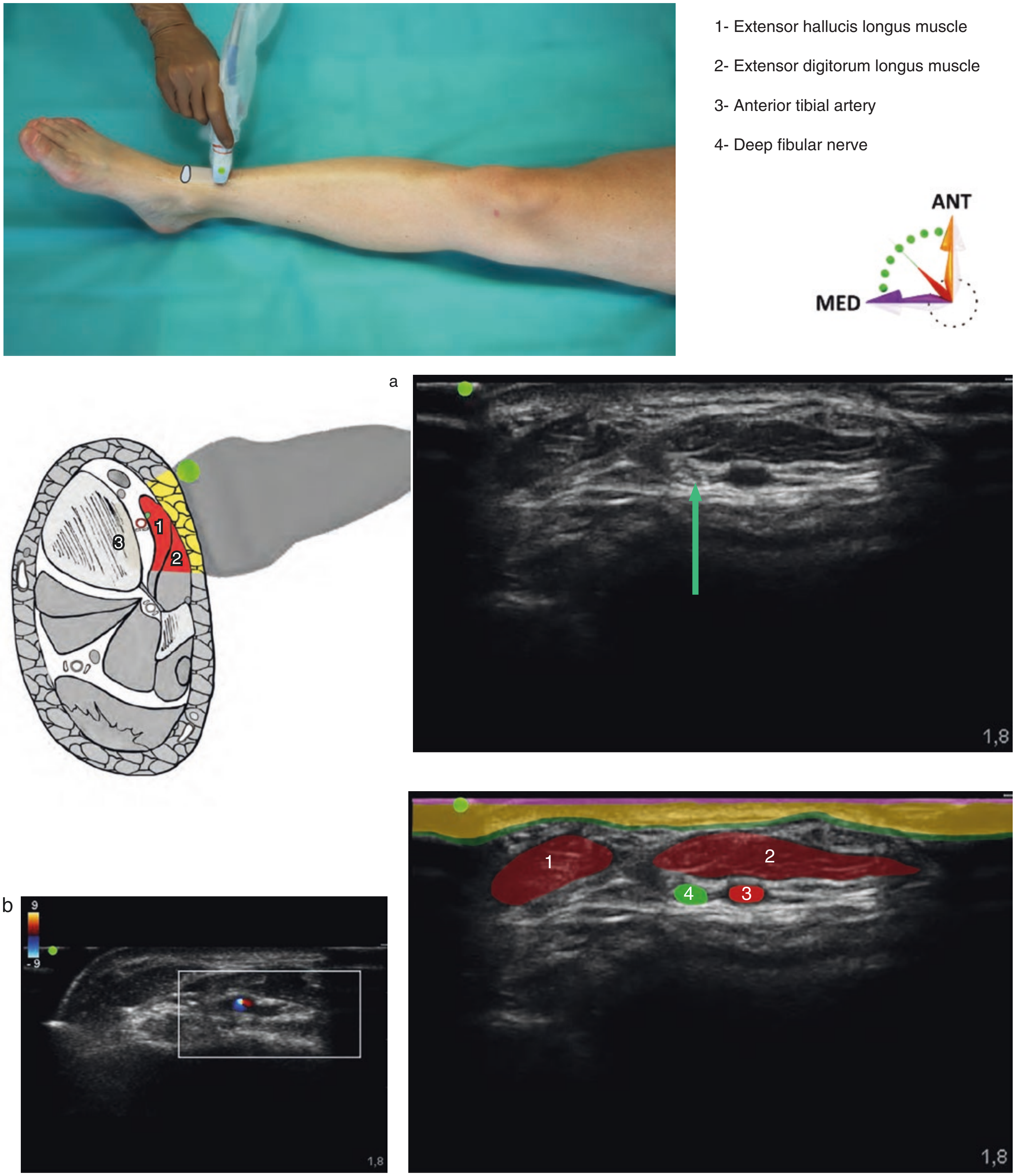

1- Extensor hallucis longus muscle
2- Extensor digitorum longus muscle
3- Anterior tibial artery
4- Deep fibular nerve
ANT
MED
a
1
2
3
1,8
b
9
- 9
1,8
1
2
4
3
1,8

Figure Fi16. (**a**) Ultrasound transversal views of the deep fibular nerve at the ankle level. An anatomical variation showing a deep fibular nerve at an uncommon medial position. (**b**) Doppler mode view.

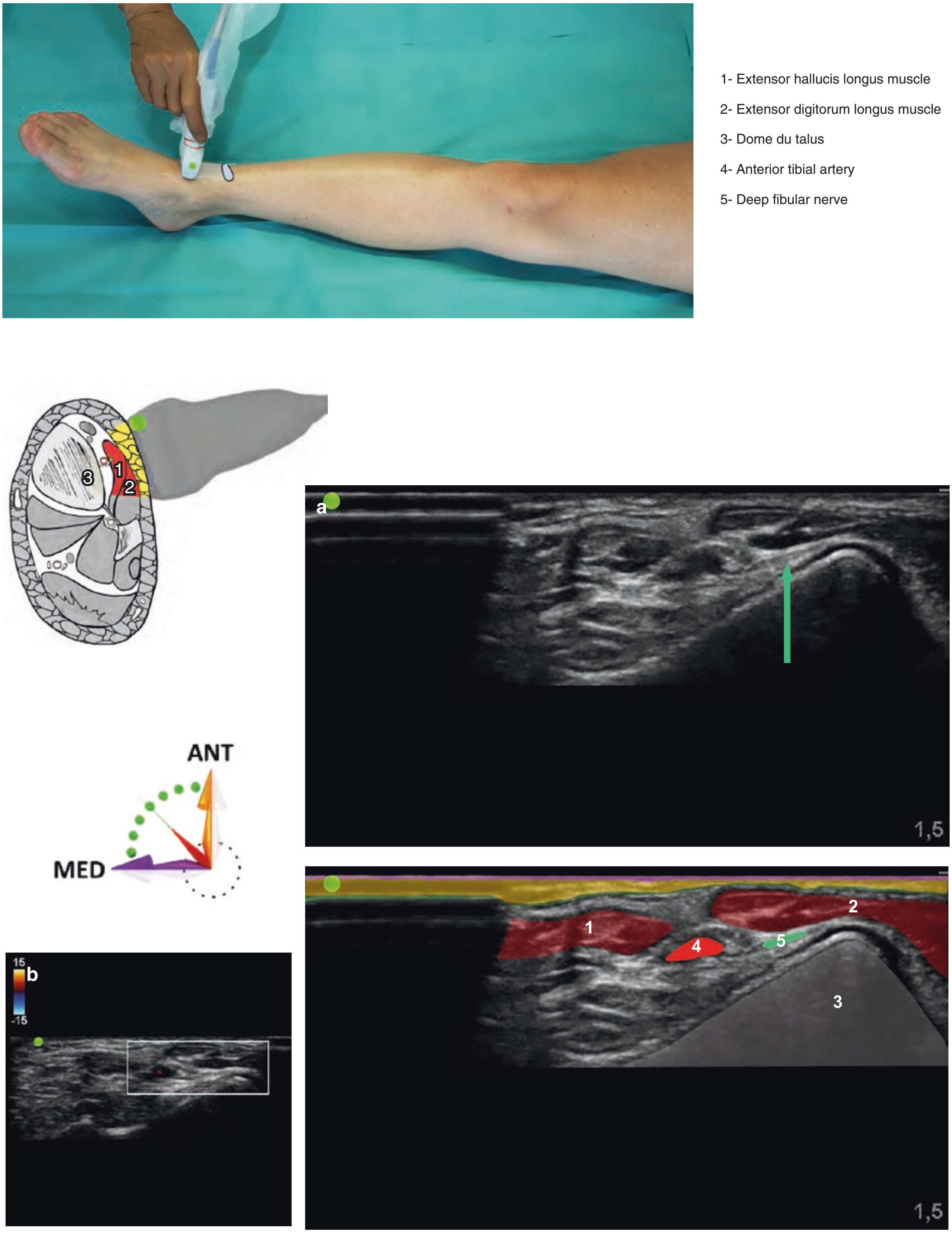

1- Extensor hallucis longus muscle
2- Extensor digitorum longus muscle
3- Dome du talus
4- Anterior tibial artery
5- Deep fibular nerve
3
1
2
ANT
MED
a
1,5
1
2
3
4
5
1,5
15
b
-15

Figure Fi17. (**a**) Ultrasound transversal views of the deep fibular nerve at the inferior part of the extensor retinaculum. (**b**) Doppler mode view.

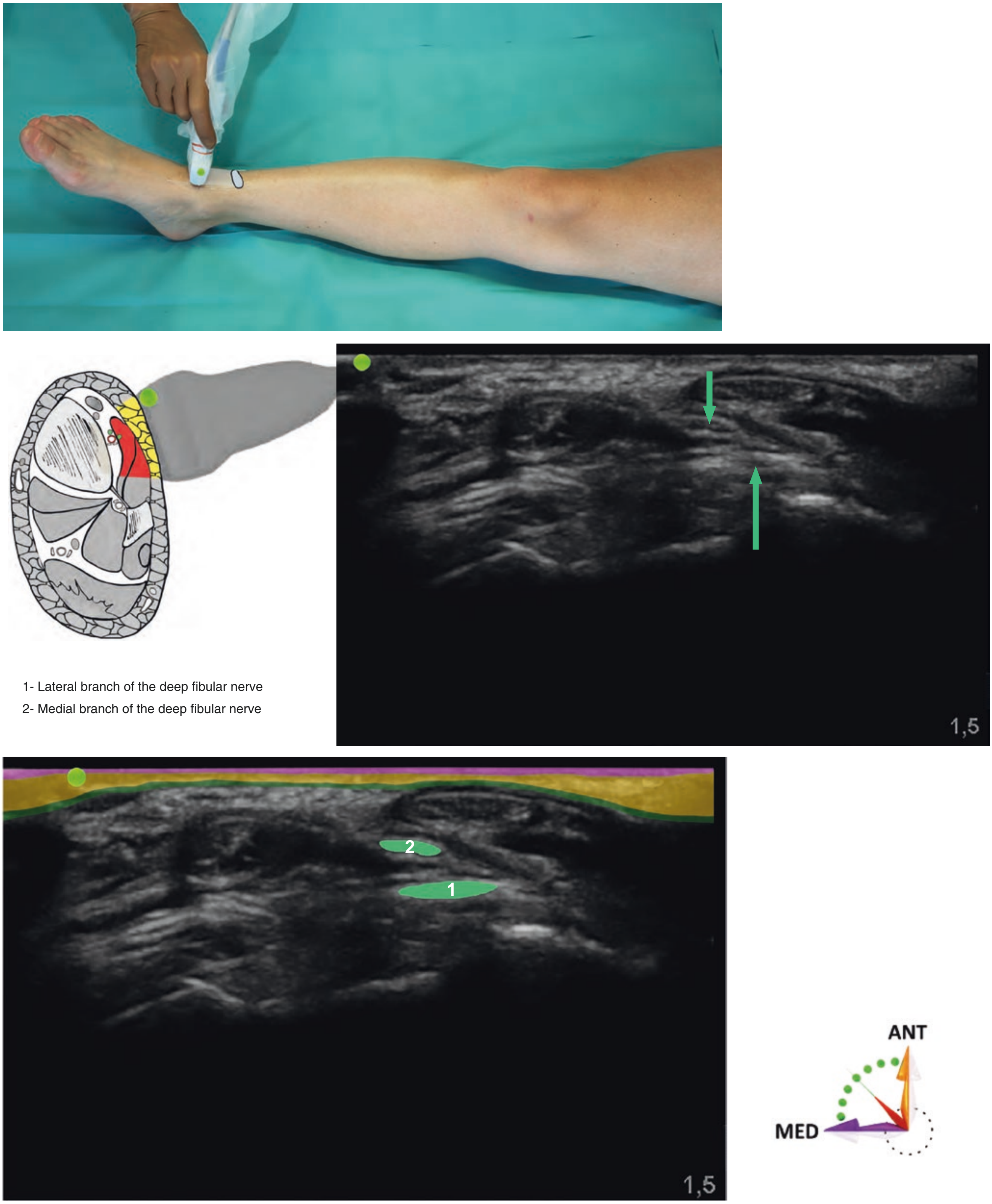

1- Lateral branch of the deep fibular nerve
2- Medial branch of the deep fibular nerve
1,5
2
1
1,5
ANT
MED

Figure Fi18. Ultrasound transversal views of the deep fibular nerve at the level of its division into lateral and medial branches.

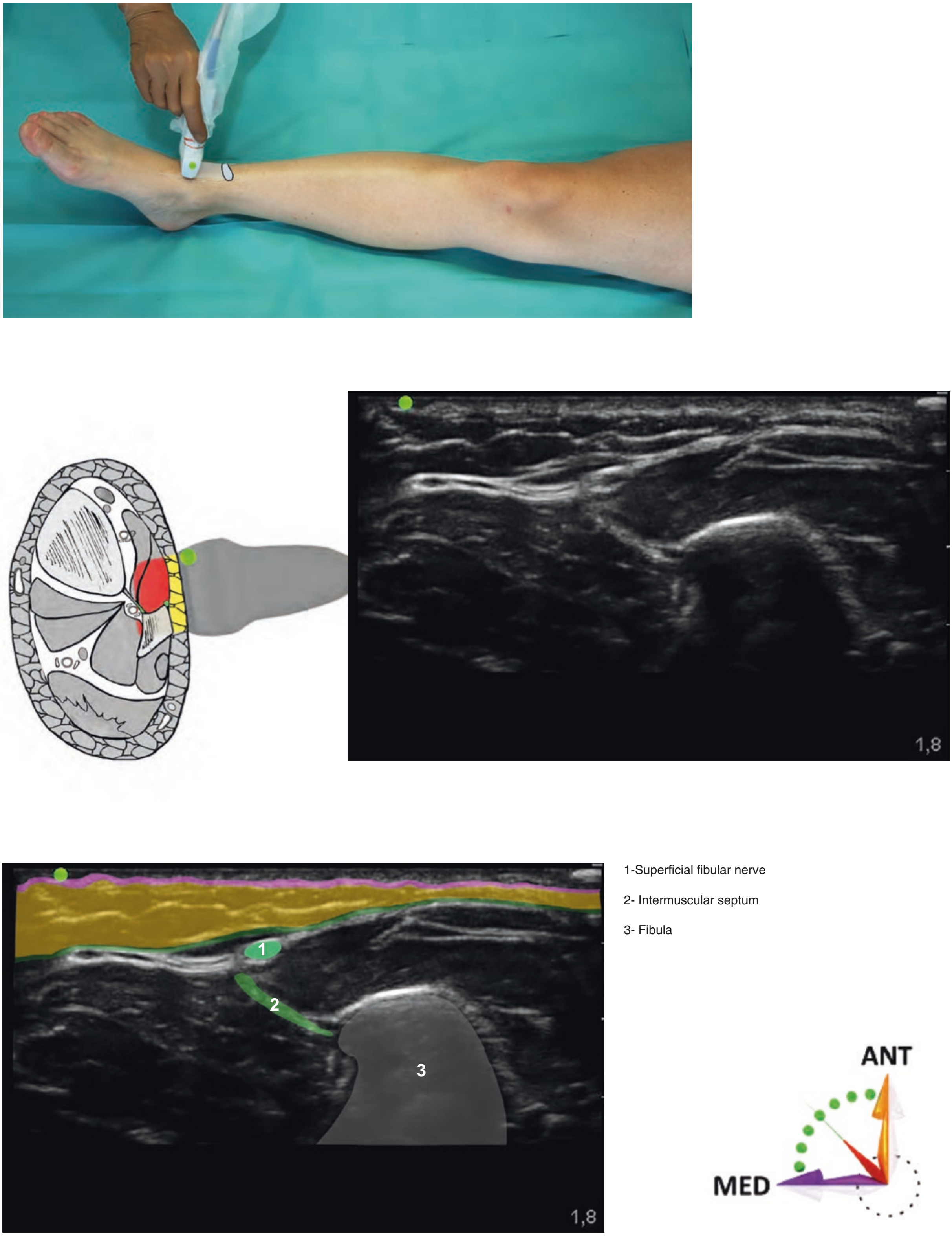

1,8
1
2
3
1,8
1-Superficial fibular nerve
2- Intermuscular septum
3- Fibula
ANT
MED

Figure Fi19. Ultrasound transversal views of the superficial fibular nerve at the distal third of the leg.

Interventional Procedure

Infiltration/Test Block at the Fibula Neck

Technique

Given the relatively superficial nature of the nerve at this level, it is ideal to remain in a flat position, and the infiltration is carried out from back to front or vice versa. After ultrasound identification of the nerve described above at the fibula neck, the “in plane” position of the infiltration needle is maintained. The needle insertion point is at the upper or cephalic end of the probe, which allows the tangential needle to arrive, but with very smooth obliquity in contact with the fibular nerve. This method reduces the trauma to adjacent muscles. For the diagnostic test block, a small volume of local anaesthetic, <1 mL, should be used.

Surgical PNS Implantation at the Fibula Neck

Technique

The patient positioning and the surgical approach to the nerve are strictly identical to the above description of nerve decompression. Once the nerve is exposed, the lead will be sutured to the perineural tissues, just behind the fibula neck, to preserve flexibility, especially if the patient is thin. After creating a safety loop, the distal end of the lead will be tunnellized in the posterior region of the knee, laterally and connected to its provisional extension with systematic verification of per-operative impedances. Later, the tunnelling will be repeated from this region, up to the generator pocket, in the upper and lateral region of the adjacent buttock.

The example used in this book concerns the identification for an infiltrative action in the tarsal tunnel, where the nerve is easily identifiable (Figure Fi20).

Infiltration/Test Block at the Tarsal Tunnel

Indication

It is interesting to explore this nerve above, facing and below the tarsal tunnel, and finally where the nerve divides, because it is the clinic that dictates the level of infiltration at which the nerve will be located. In the context of a suspected tarsal tunnel syndrome, ultrasound is an easily accessible and highly relevant diagnostic tool.

Technique

The patient is positioned in supine position, with the foot resting on the heel and in undifferentiated plantar flexion.

The ultrasound probe will be positioned 3 cm above the ankle to find the nerve in its path between the long extensor muscle of the hallux and the extensor digitorum longus muscle of the toes.

The probe is positioned in the axial section, preferring the in-plane technique, from medial to lateral. In case the “out of plane” probe position is preferred, it is important to insist on the centring of the nerve, which must be in the middle of the screen throughout the procedure.

RFP

It remains possible when no compressive aetiology is found.

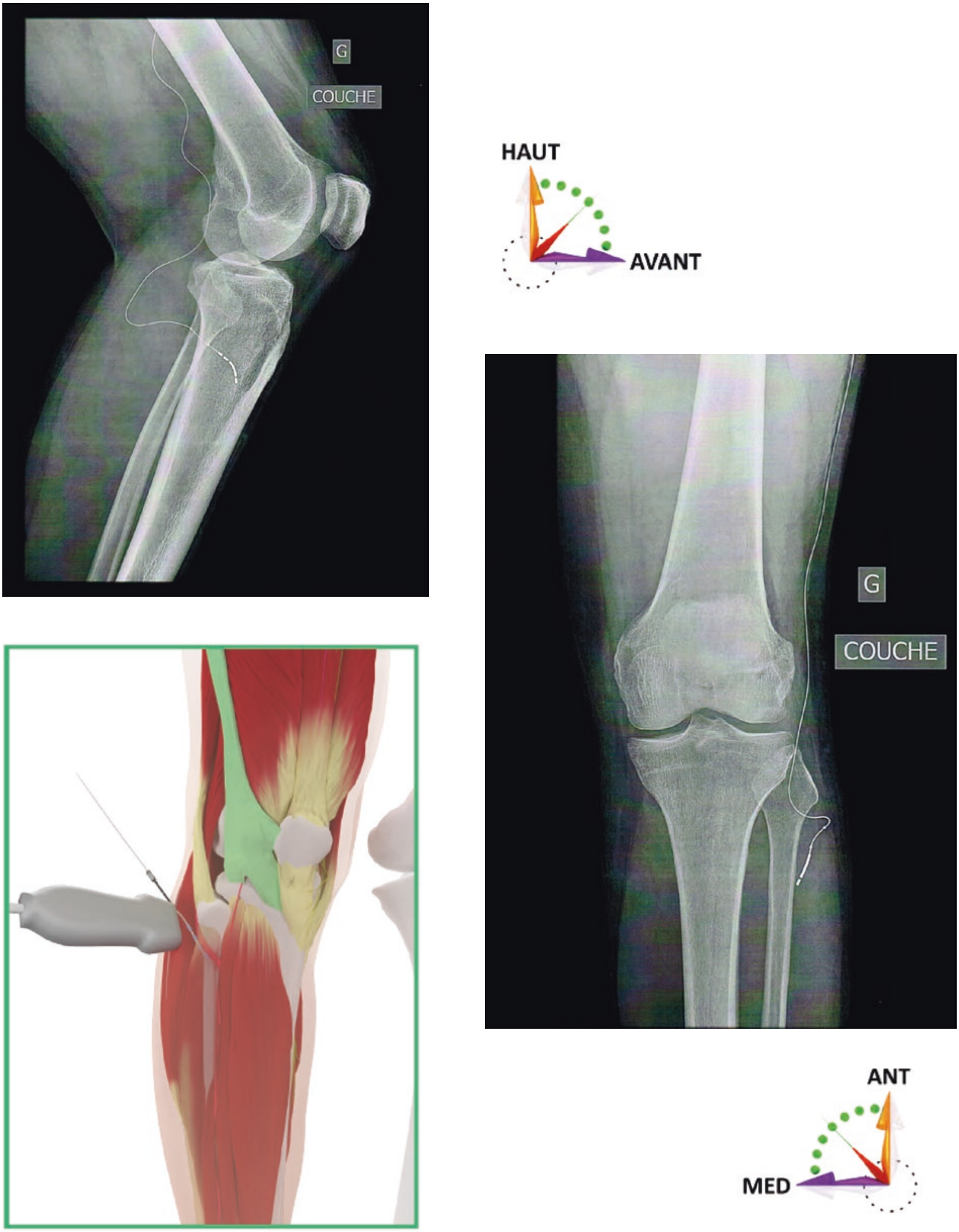

G
COUCHE
HAUT
AVANT
G
COUCHE
ANT
MED

Figure Fi20. Post-op X-ray showing a fibular nerve stimulation at the fibula's neck.

Surgical Procedure

Surgical Indications

- Nerve exploration or repair after direct blunt trauma.
- Removal of a tumour lesion.
- Lesions may also be secondary to external compressions such as hematoma or a cast on the upper part of the boot during orthopaedic treatment of leg fractures.
- Ductal fibular nerve syndrome under the fibula neck (see “Pathology” section, above).

In the Leg

Skin Incision

The landmark is located one finger crosswise outside the fibula neck. The incision extends upwards and backwards. The lower limb is in slight flexion, internal rotation and adduction to move up to the lateral edge of the popliteal fossa if necessary. The incision continues downwards in an oblique forward direction following the nerve at its deep branch.

Nervous Exposure

The fascia is split according to the skin incision to reveal the nerve just outside the biceps femoris muscle, in front of and above the lateral head of the gastrocnemius muscle. Care must be taken not to damage the lateral sural cutaneous nerve that goes to the calf. The nerve is then followed to the fibula neck, where it enters a muscle tunnel developed in the peroneus longus muscle. Section of the peroneus longus muscle elucidates division of the fibular nerve into superficial and deep fibular nerves, which can be followed respectively (Figure Fi21).

Technical Pitfalls

- Excessive interruption of distal venous drainage (postoperative oedema of the limb)
- Retractable scar in case of high skin tensions in this region

PNS by Surgery at the Fibula Neck

The patient’s installation and the surgical approach to the nerve are strictly identical to the above description of nerve decompression. Once the nerve is exposed, a lead will be sutured to its spine, just behind the fibula neck, to keep the tissues flexible, especially if the patient is thin. After creating a safety loop, the distal end of the lead will be tunnellized in the posterior region of the knee, laterally and connected to its provisional extension with systematic verification of peroperative impedances. Later, the tunnelling will be repeated from this region, up to the generator cubicle, in the upper and lateral region of the adjacent buttock.

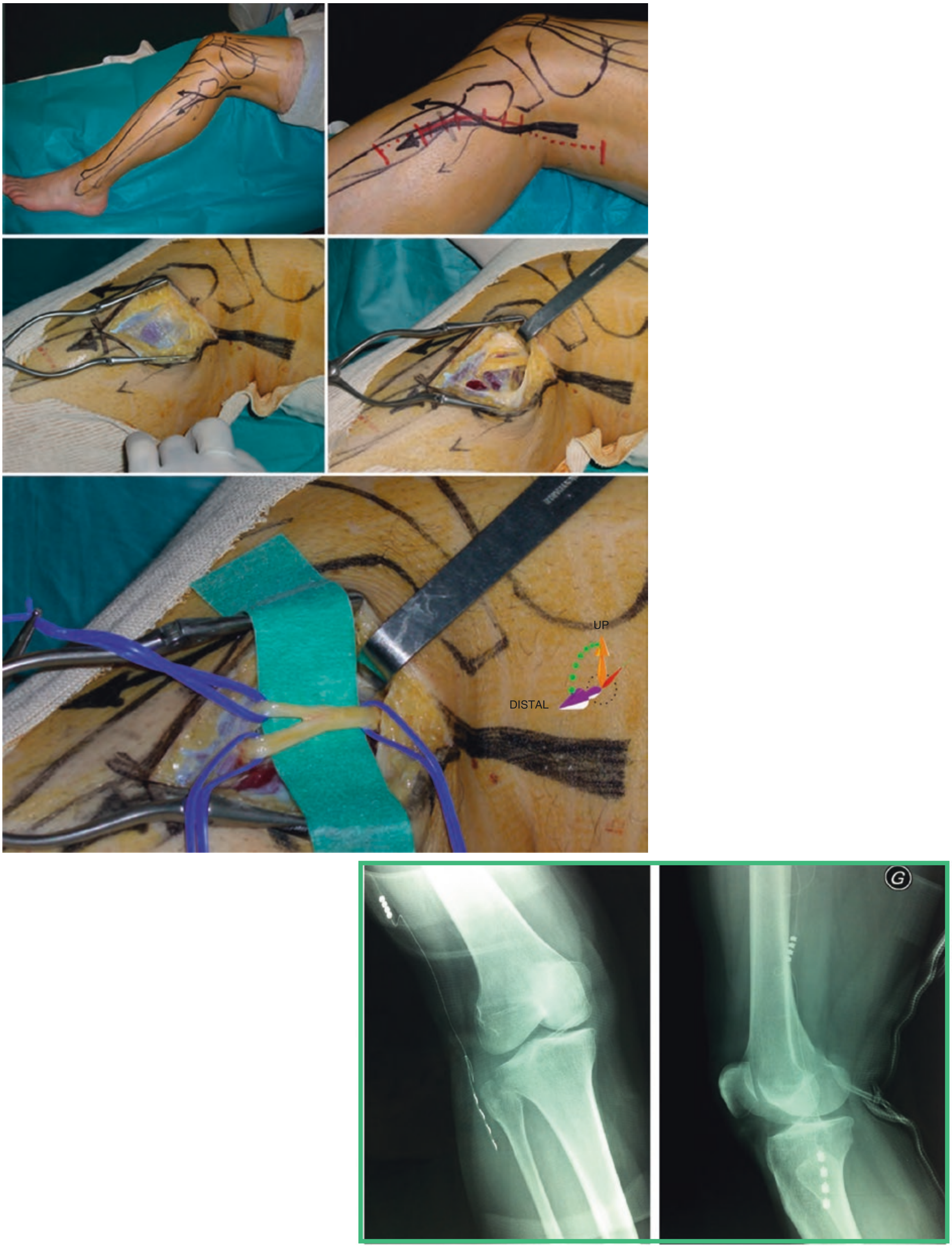
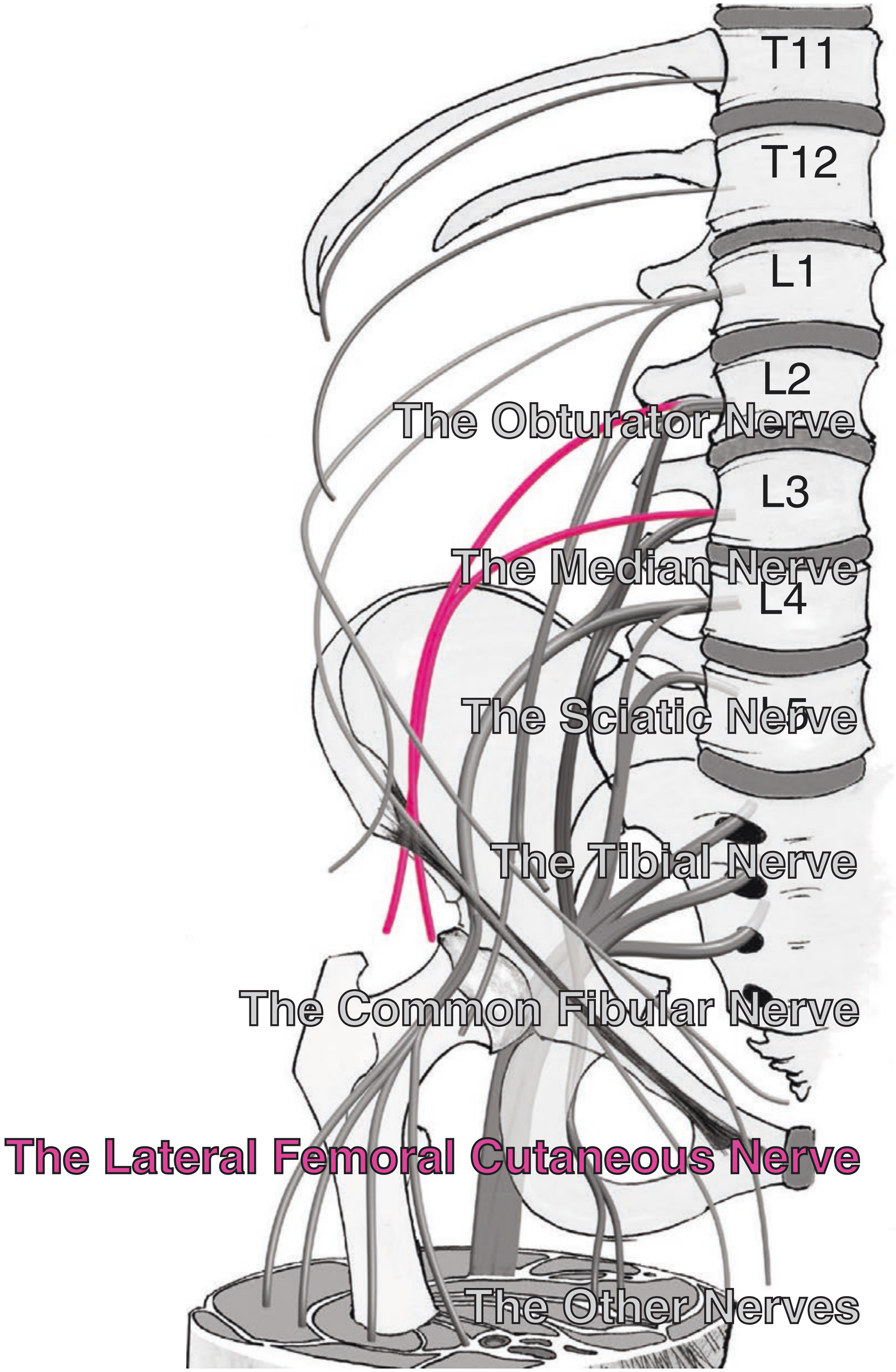


Figure Fi21. Surgical approach of the fibular nerve at the leg level, anterolateral view. Post-op X-ray showing a fibular nerve stimulation at the fibula's neck.


T11
T12
L1
L2
The Obturator Nerve
L3
The Median Nerve
L4
The Sciatic Nerve
L5
The Tibial Nerve
The Common Fibular Nerve
The Lateral Femoral Cutaneous Nerve
The Other Nerves

LFC

The Lateral Cutaneous Nerve

Morphological Data

The lateral femoral cutaneous nerve is a nerve with a sensitive function only. It innervates the lateral area of the buttock and of the thigh after going through the iliac fossa.

Origin

The lateral femoral cutaneous nerve is a collateral branch of the lumbar plexus. It is constituted of the L2 roots and of the branch which unites the L2 and L3 roots (Figures. LFC1 and LFC2). It originates above the femoral and obturator nerves, which are terminal branches of the lumbar plexus.

Path

The lateral femoral cutaneous nerve goes in front of the genitofemoral nerve and then away towards the iliac fossa in order to join the notch between the anterior iliac spines of the hip bone (Figures LFC2 and LFC3). It emerges on the lateral border of the psoas, goes along the quadratus lumborum whilst passing in front of its distal insertion and then goes into a division of the aponeurosis of the iliacus muscle.

It leaves the pelvis through an osteofibrous tunnel slightly below and medially in relation to the anterior superior iliac spine. It then goes under the inguinal ligament and penetrates into the thigh under the aponeurosis of the quadriceps femoris muscle. Finally, it crosses the sartorius muscle from the front and splits into several terminal branches (Figure LFC3).

The lateral femoral cutaneous nerve has a close relation with the anterior superior iliac spine, which is the main anatomical landmark used in surgery. This nerve is generally found a finger's width away towards the inside of the anterior superior iliac spine. It can go behind, through or in front of the inguinal ligament and generally places itself medially in relation to the sartorius.

Neurovascular Relations

At its origin, the lateral femoral cutaneous nerve faces the external iliac vessels from a distance.

When going along the iliacus muscle, right before the anterior superior iliac spine, the lateral femoral cutaneous nerve is crossed in front by the deep circumflex iliac artery, which is a collateral branch of the external iliac artery.

At the level of the inguinal ligament, the superficial circumflex iliac vessels can be found, the artery of which is a branch of the femoral artery (Figure LFC4).

Terminal Branches

The lateral femoral cutaneous nerve ends when it crosses the anterior face of the sartorius muscle, which originates on the anterior superior iliac spine. It splits at this level into two terminal branches: the anterior and posterior branches (Figures LFC2 and LFC6).

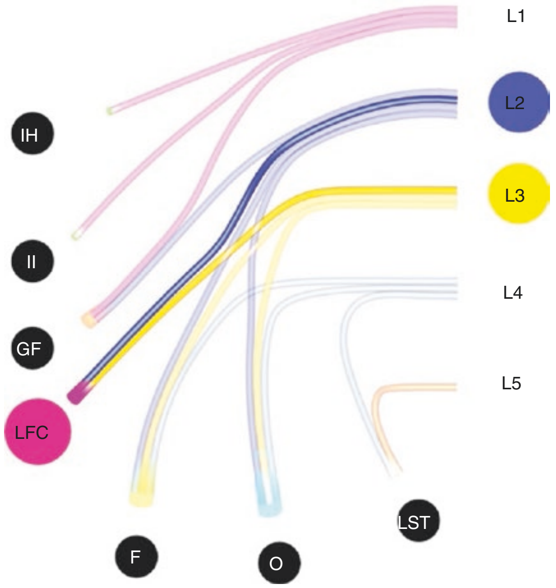


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Figure LFC1. Origin of the lateral femoral cutaneous nerve.

Electronic Supplementary Material The online version of this chapter (https://doi.org/10.1007/978-3-030-49179-6_18) contains supplementary material, which is available to authorized users.

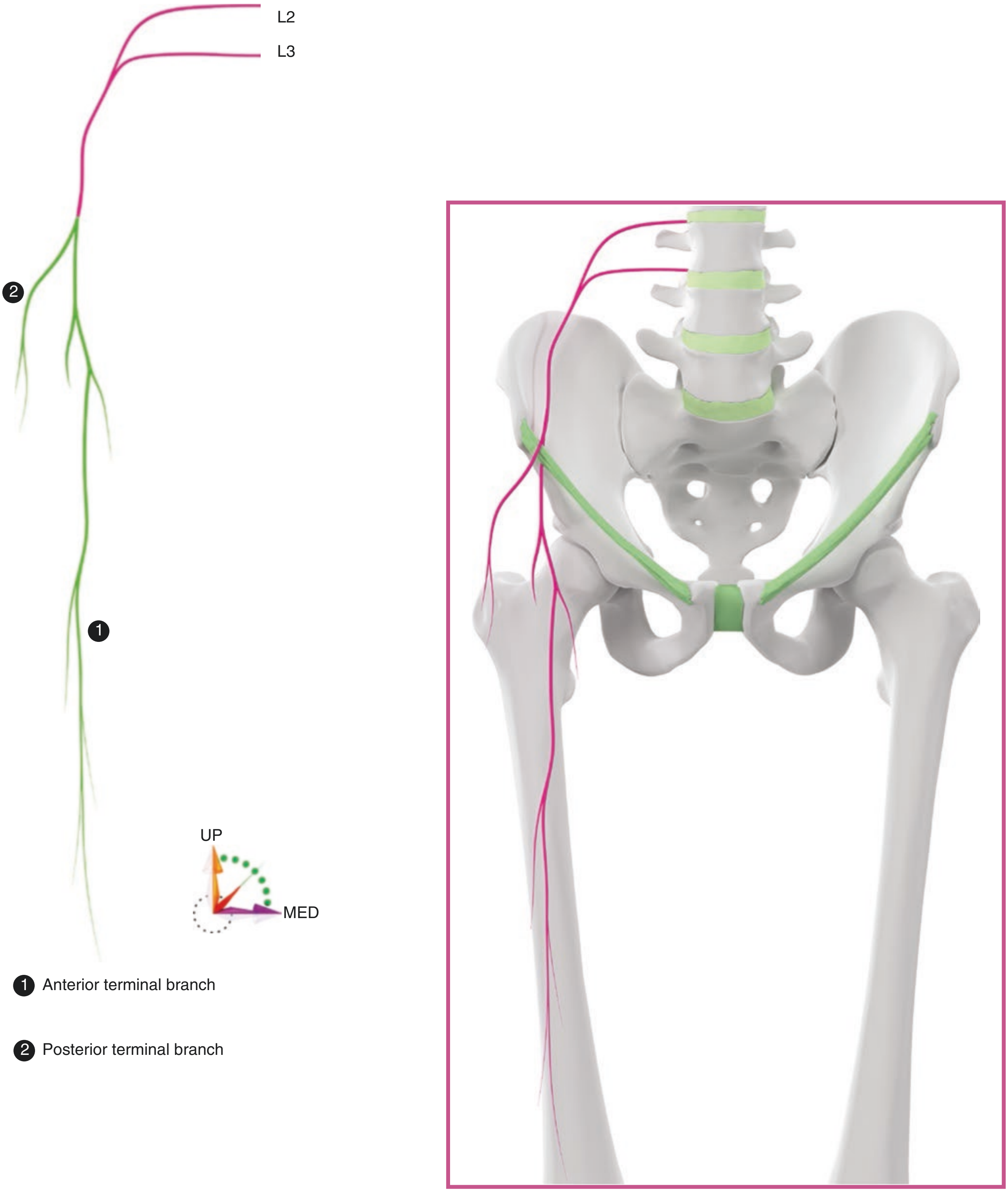
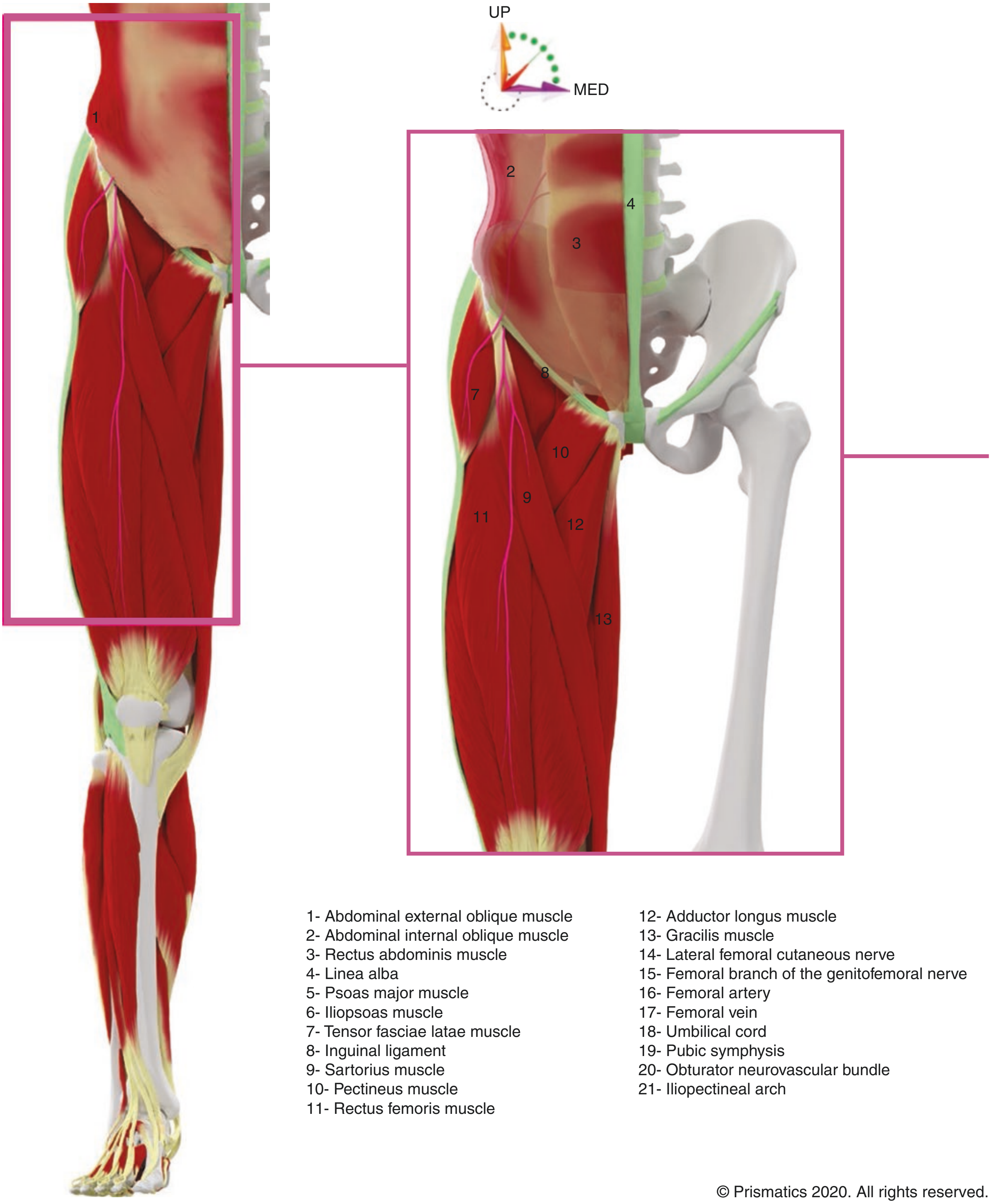

L2
L3
2
1
UP
MED
1 Anterior terminal branch
2 Posterior terminal branch

Figure LFC2. Topographical distribution of the lateral femoral cutaneous nerve and its relations with bones.



1- Abdominal external oblique muscle
2- Abdominal internal oblique muscle
3- Rectus abdominis muscle
4- Linea alba
5- Psoas major muscle
6- Iliopsoas muscle
7- Tensor fasciae latae muscle
8- Inguinal ligament
9- Sartorius muscle
10- Pectineus muscle
11- Rectus femoris muscle
12- Adductor longus muscle
13- Gracilis muscle
14- Lateral femoral cutaneous nerve
15- Femoral branch of the genitofemoral nerve
16- Femoral artery
17- Femoral vein
18- Umbilical cord
19- Pubic symphysis
20- Obturator neurovascular bundle
21- Iliopectineal arch

Figure LFC3. Muscular relations of the lateral femoral cutaneous nerve at the iliac fossa and thigh.

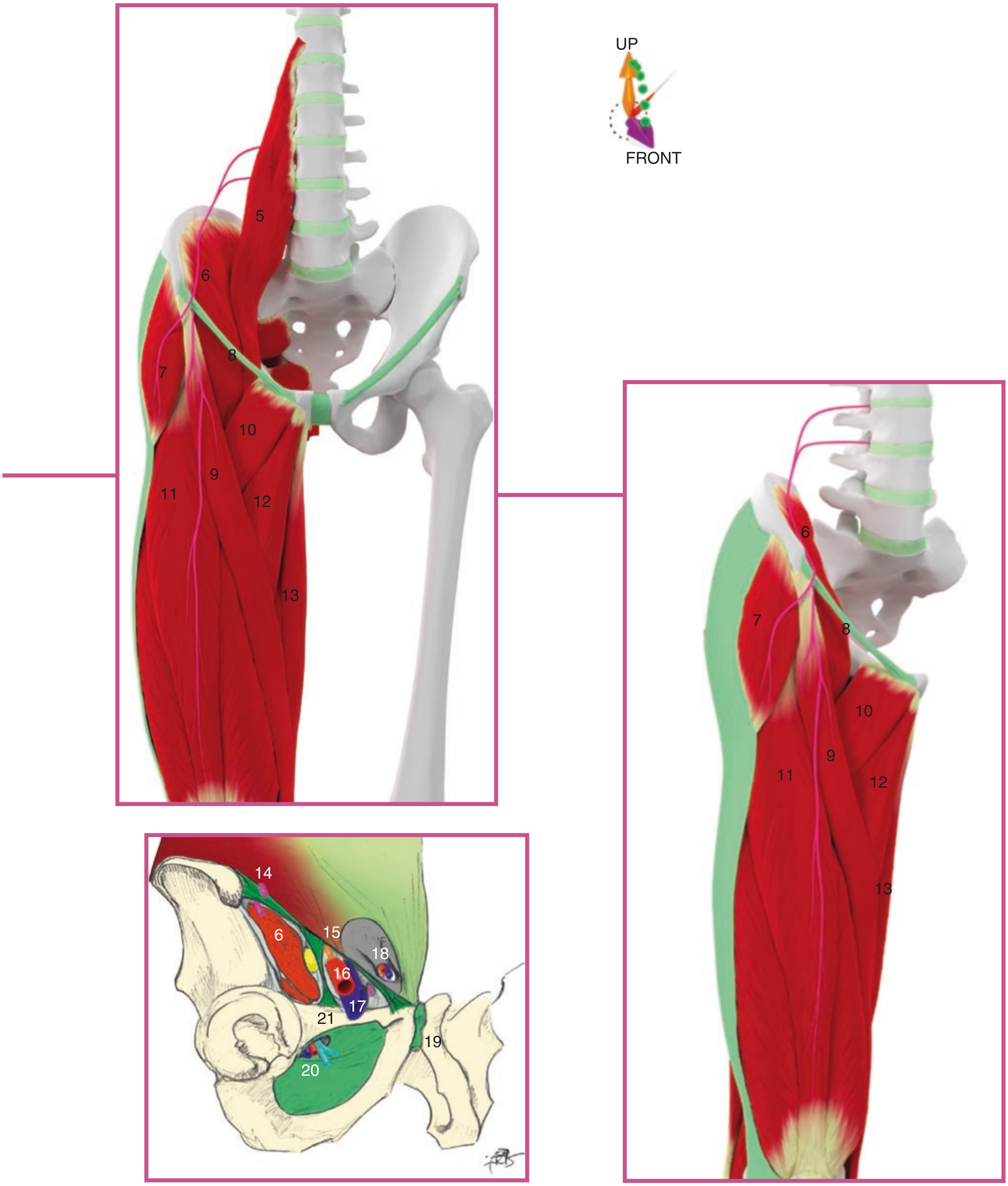

UP
FRONT
5
6
7
8
10
9
11
12
13
6
7
8
10
9
11
12
13
14
6
15
18
16
17
21
19
20

Figure LFC4. Muscular relations of the lateral femoral cutaneous nerve at the iliac fossa and at the thigh (from superficial to deep) (Drawing by P. Rigoard, based on Sobotta).

The anterior branch innervates the anterolateral area of the thigh, under the territories of the iliohypogastric and genitofemoral nerves. The innervation territory of the anterior branch ends at the upper part of the knee (Figure LFC5).

The posterior branch goes towards the greater trochanter. It innervates the posterolateral face of the buttock and the superior lateral part of the thigh (Figure LFC5).

Sensitive Function

It takes charge of the sensitive innervation of the anterolateral face of the thigh down to the knee. Its territory is limited medially, in front by the sensitive territory of the femoral nerve, behind and above by the territories of the cluneal nerves and below by the territory of the posterior femoral cutaneous nerve.

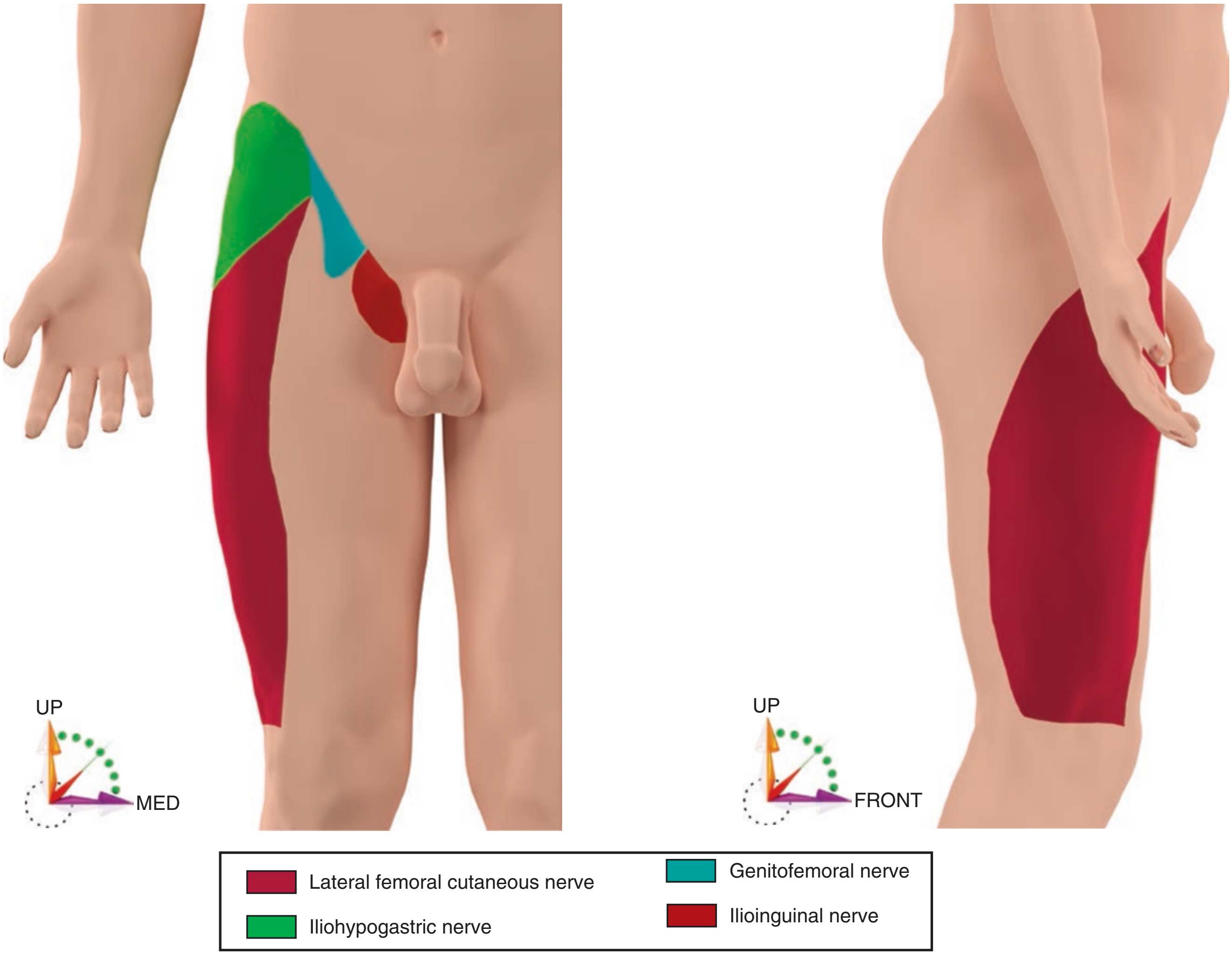
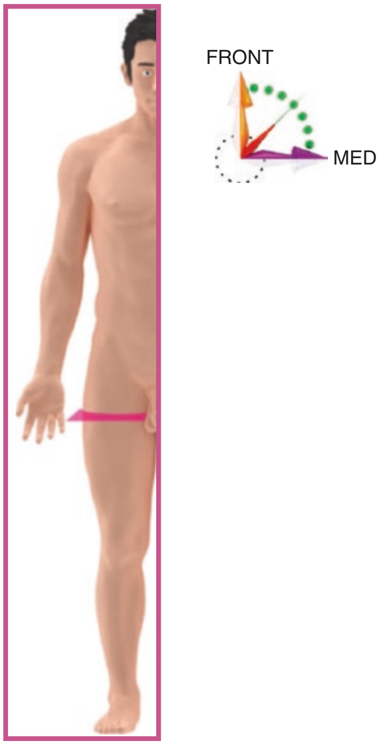
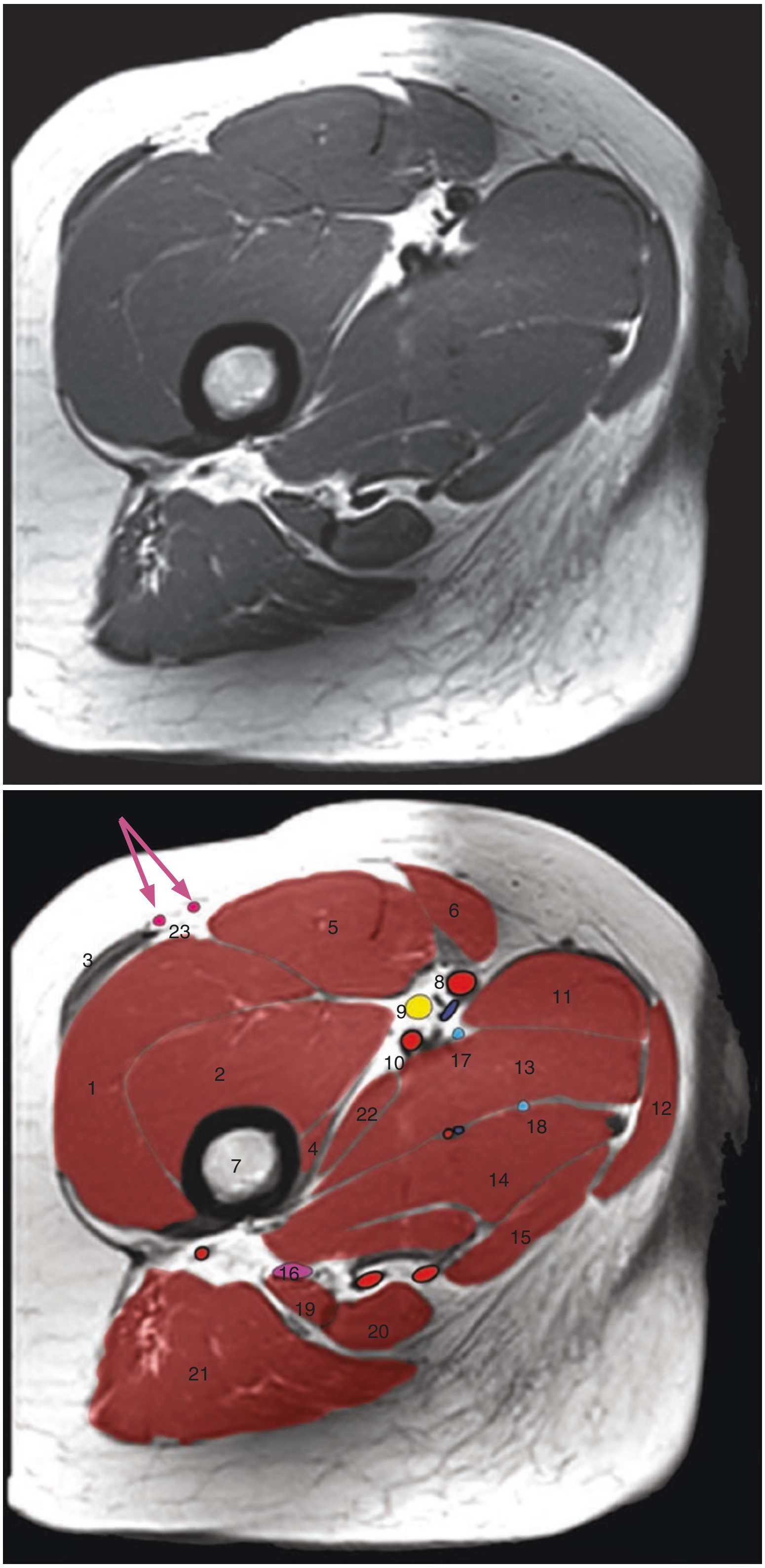

UP
MED
UP
FRONT
🟥 Lateral femoral cutaneous nerve
🟩 Iliohypogastric nerve
🟦 Genitofemoral nerve
🟥 Ilioinguinal nerve

Figure LFC5. Sensitive innervation of the lateral femoral cutaneous nerve.





1- Vastus lateralis muscle
2- Vastus intermedius muscle
3- Tensor fasciae latae muscle
4- Vastus medialis muscle
5- Rectus femoris muscle
6- Sartorius muscle
7- Femur
8- Femoral artery and vein
9- Femoral nerve
10- Deep femoral artery and vein
11- Adductor longus muscle
12- Gracilis muscle
13- Adductor brevis muscle
14- Adductor magnus muscle
15- Semimembranosus muscle
16- Sciatic nerve
17- Anterior branch of the obturator nerve
18- Posterior branch of the obturator nerve
19- Tendon of the biceps femoris muscle
20- Tendon of the semitendinosus muscle
21- Gluteus maximus muscle
22- Pectineus muscle
23- Lateral femoral cutaneous nerve

Figure LFC6. MRI scans at the proximal third of the thigh through the lateral femoral cutaneous nerve and its terminal branches.

Pathology

Meralgia Paraesthetica

The lateral femoral cutaneous nerve, a collateral branch of the lumbar plexus, is solely sensitive. It goes along the iliac fossa whilst staying in contact with the iliacus muscle and then goes out of the pelvis between the anterior iliac spines.

It innervates the superior part of the lateral face of the thigh.

Aetiology

- Compression: An entrapment neuropathy can occur when the nerve comes out of the pelvis, in contact with the notch between the anterior iliac spines.

Clinical Significance

The signs are exclusively sensitive. The pain often appears suddenly and is bilateral in 10% of cases. This pain can have a neuropathic connotation and can be linked with paraesthesiae. The disorders concern the innervation territory of the lateral femoral cutaneous nerve. They can increase in strength during night-time or during prolonged standing and can be relieved by flexion of the thigh on the body.

The pain is increased by the extension of the leg; progressively, a hypoesthesia settles in the painful territory.

Amongst the triggering factors, wearing clothes that are too tight (“skinny pants syndrome”) is notable, along with the stresses that are applied on the abdominal wall: pregnancy, obesity (Figure LFC7), persistent muscle contractions where the body and lower limb meet, such as in coxarthrosis.

Clinical examination can uncover a hypoesthesia in the painful area and, more rarely, trophic disorders with hair loss.

It is important to note that Leri’s sign cannot be found upon thigh extension. However, Tinel’s sign can be performed at the level of the iliac spine; the knee reflex occurs and remains symmetrical.

Clinical diagnosis can be confirmed by EMG (difficult) and anaesthetic nerve block.

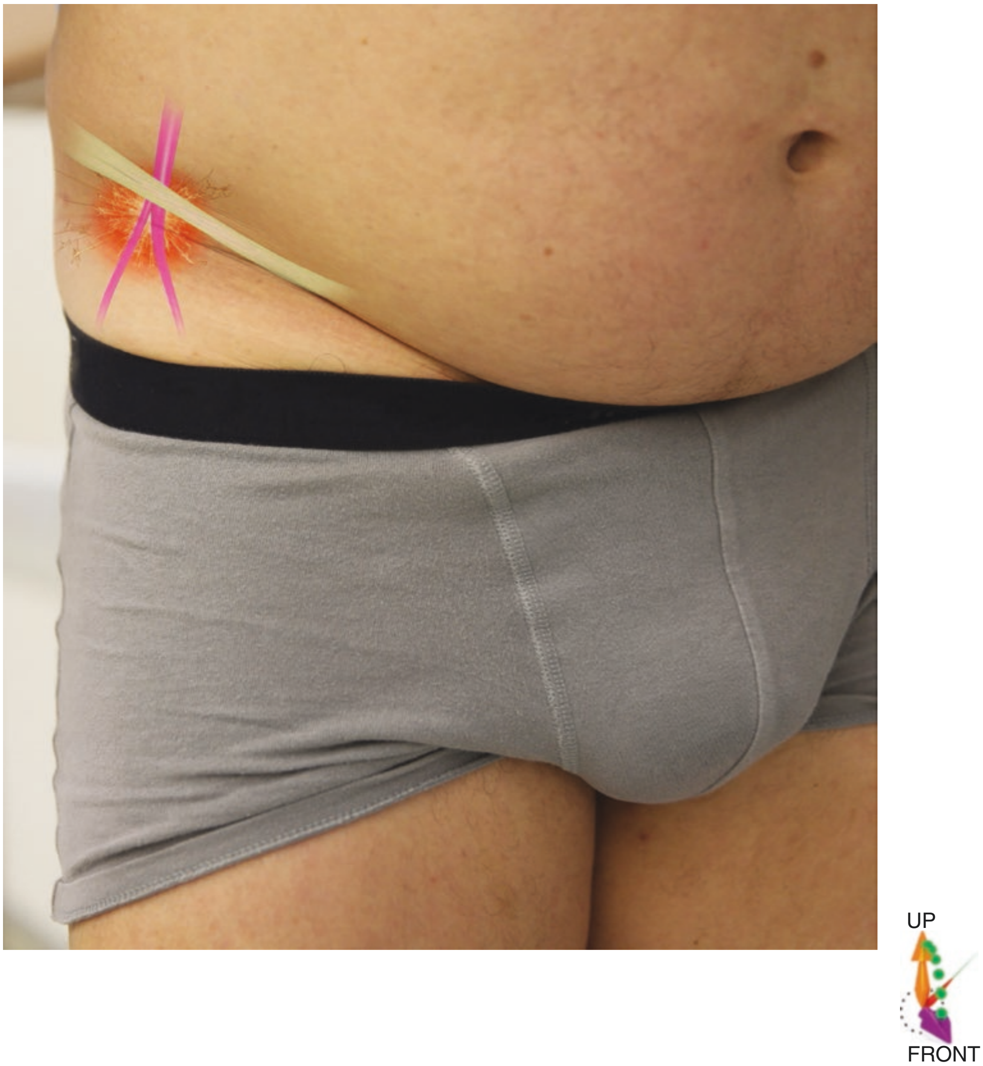


Figure LFC7. Entrapment neuropathy of the lateral femoral cutaneous nerve which appeared in the aftermath of an important weight loss (skinny pants syndrome).

Morphological Data: Sono Anatomy

Installation

The patient is in supine position, with a slight external rotation of the lower limb, as in sono-anatomical exploration of the femoral nerve.

Equipment and Location

- Probe type: linear, 5–12, 6–13 MHz
- Probe axis: transverse

Ultrasound Procedure

The probe is initially placed in the inguinal flexion fold, facing the femoral nerve and femoral artery. Use of colour Doppler and pressure/depression movements allows identification of vascular structures, particularly the femoral artery located within.

The probe is then slowly moved in a lateral direction to observe successively in axial section the sartorius muscle, and then the adjacent and more lateral tensor fasciae latae muscle.

With regard to their juxtaposition, we discover the corresponding nerve structures within the aponeurotic duplications of the fascia latae. It can be either the trunk of the lateral cutaneous nerve of the thigh or its branches of ventral and dorsal division, and sometimes collateral (Figures LFC8–LFC10).

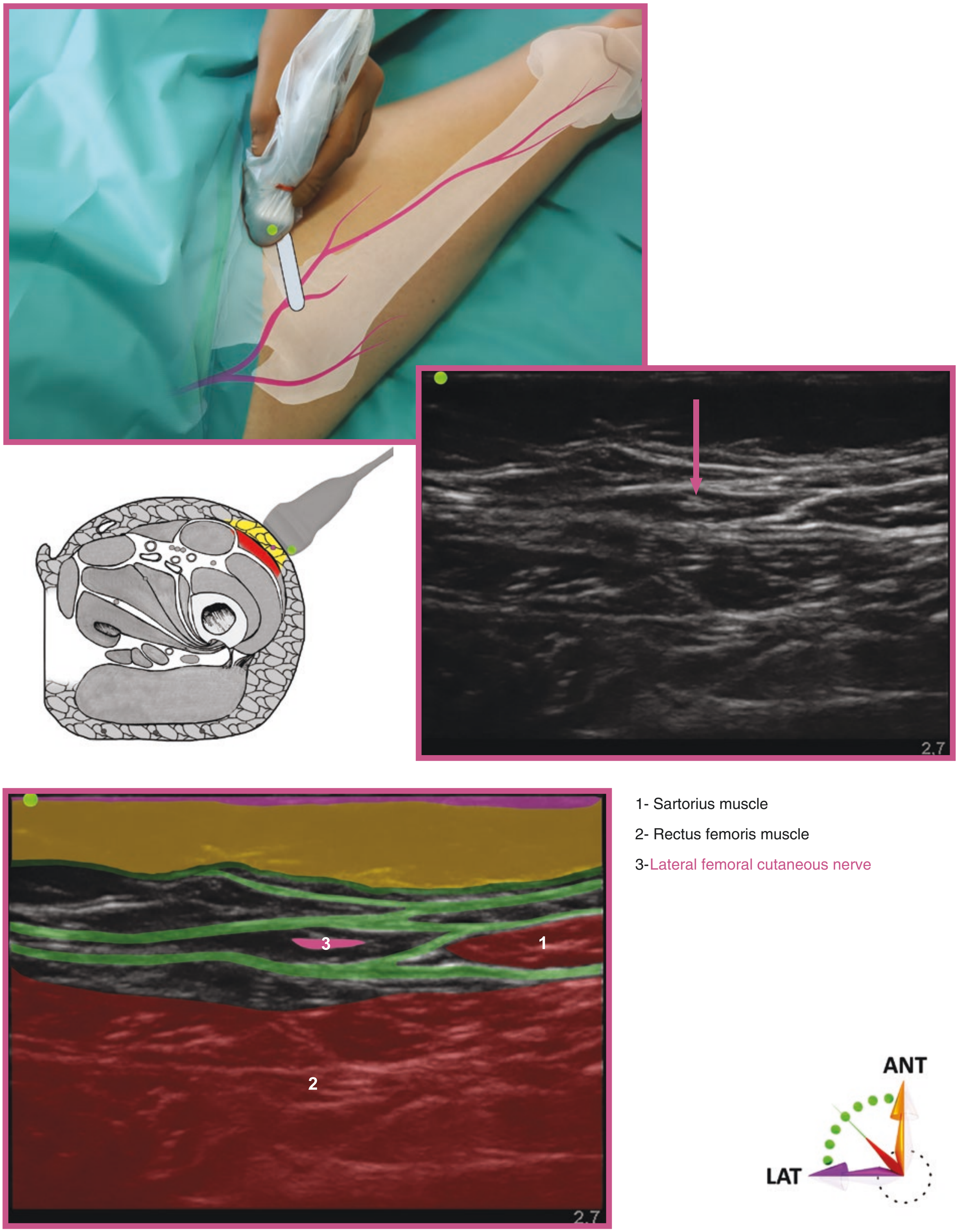
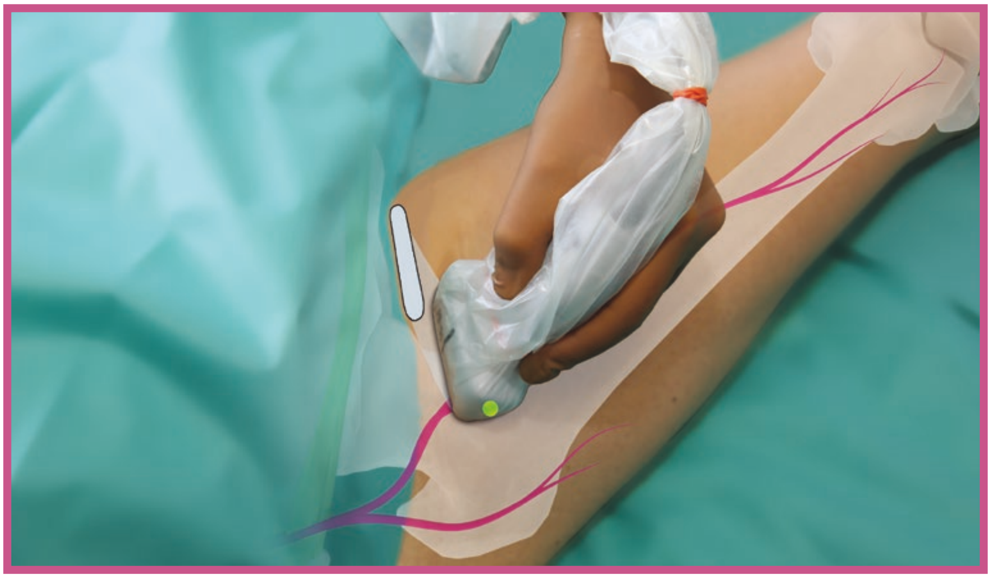

2.7
3
1
2
2.7
1- Sartorius muscle
2- Rectus femoris muscle
3-Lateral femoral cutaneous nerve
ANT
LAT

Figure LFC8. Ultrasound transversal views of the lateral femoral cutaneous nerve below the level of the anterior superior iliac spine.



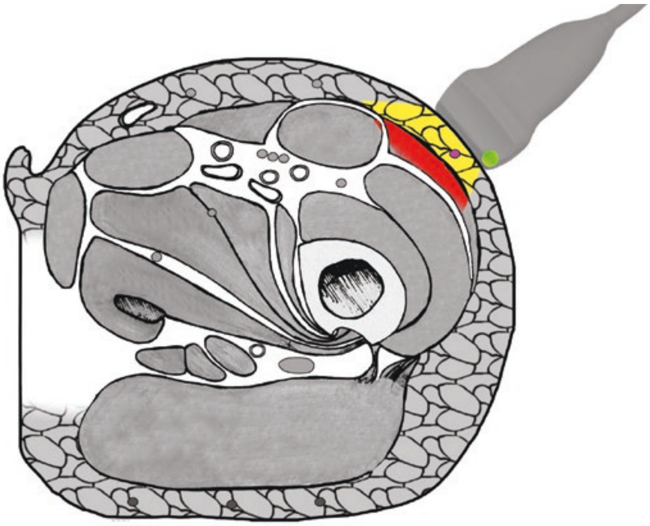
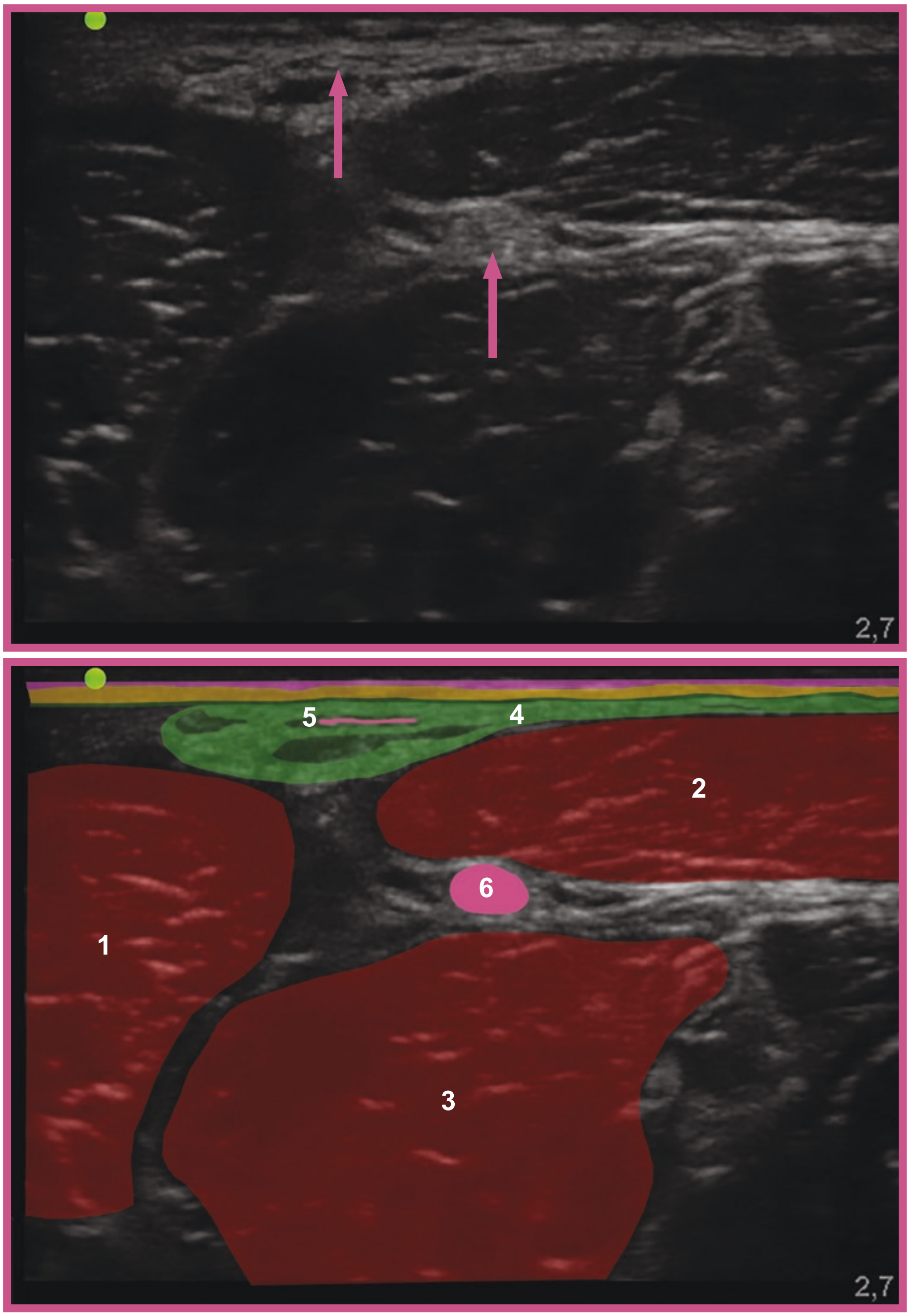
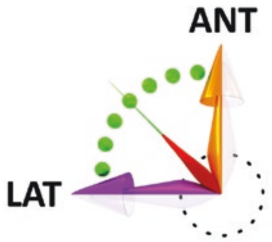


Figure LFC9. Ultrasound probe position of the lateral femoral cutaneous nerve division into anterior and posterior branches (abnormal and hypertrophied lateral femoral cutaneous nerve).





1- Tensor fasciae latae muscle
2- Sarorius muscle
3- Rectus femoris muscle
4- Fascia iliaca
5- Lateral femoral cutaneous nerve (anterior branch)
6- Lateral femoral cutaneous nerve (posterior branch)

Figure LFC10. Ultrasound transversal views of the lateral femoral cutaneous nerve division into anterior and posterior branches (abnormal and hypertrophied lateral femoral cutaneous nerve).

Interventional Procedure

Infiltration/Test Block

Indication

Infiltration can be carried out for diagnostic or therapeutic purposes in the context of ductal nerve syndromes.

To avoid false negatives, it is important to perform a preliminary ultrasound scan to locate any proximal divisions of the nerve. Compression of the anterior branch usually results in painful projection on the thigh, which is more anterior, and the posterior branch in more lateral pain, corresponding to the true primary description of paresthesiastic meralgia.

Technique

- After ultrasound identification of the nerve described above, the needle is in the "in plane" position.
- Possibility to use the "out of plane" technique, whilst remaining very superficial—but this approach is more difficult.
- The needle progresses from lateral to medial, so as to be in contact with the nerve chamber. For a diagnostic test block, a stimulation test is performed before injection. Division of the lateral cutaneous nerve of the thigh may be more cranial above the iliac crest; the stimulation test is therefore particularly useful to ensure good coverage of the painful area.

PNS

Indication

Rebellious neuropathic pain of the lateral cutaneous thigh nerve.

Technique

- After ultrasound identification of the above-mentioned nerve, the guide needle is placed "out of plane".
- The nerve is placed in the middle of the screen with hydrolocalization/hydrodissection.
- The lead stimulation must move in a usually retrograde direction. Sometimes, for morphological reasons related to the patient, its direction can be adjusted in a craniocaudal axis.
- Given the superficial nature of the nerve, it is easy to check the correct positioning of the lead stimulation under ultrasound.
- If the patient is under light anaesthesia and hydrodissection with saline or glucose, it will be possible to perform a sensory test.
- Afterwards, the internal pulse generator can be implanted, either on the lateral surface of the thigh or in the abdominal area (Figure LFC11).

RFP

Technique

- After ultrasound identification of the above-mentioned nerve, the infiltration needle is placed "in plane".
- The needle progresses from lateral to medial, so as to be in contact with the nerve chamber.
- The stimulation is carried out after completion of a stimulation block, with the following parameters: 20 ms, 2 Hz, 0.45 V, ensuring that the temperature of the thermo-couple does not exceed 42 °C.
- Average duration of the procedure is 3–4 min.

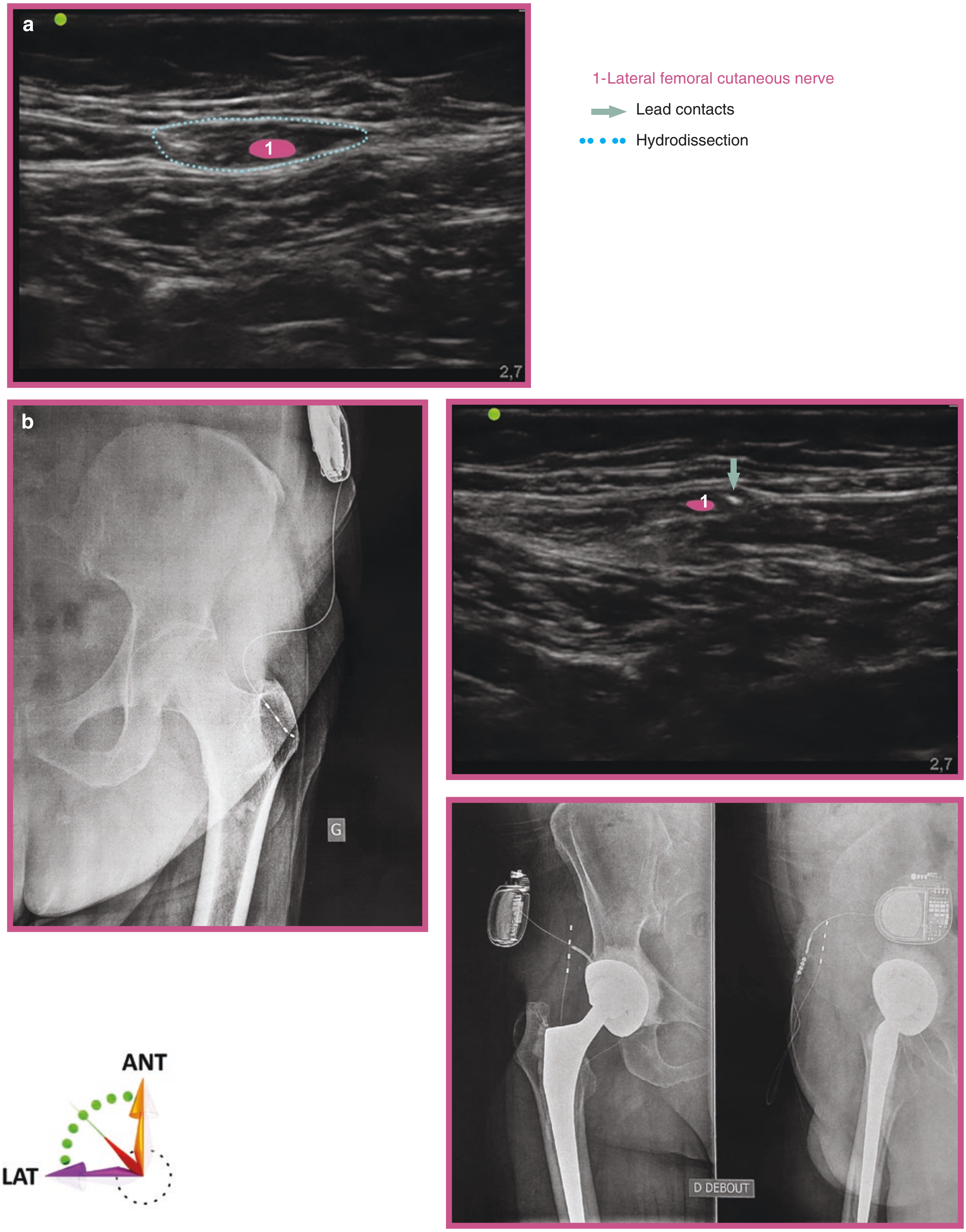

a
1
2,7
1-Lateral femoral cutaneous nerve
→ Lead contacts
•••• Hydrodissection
b
G
1
2,7
D DEBOUT
ANT
LAT

Figure LFC11. An illustrative view of lateral femoral cutaneous nerve neurostimulation. (**a**) Hydrodissection under ultrasound guidance. (**b**) Post-op X-ray showing the craniocaudal lead position.

Surgical Procedure: Lateral Femoral Cutaneous Nerve Decompression

Surgical Description

Skin Incision

The surgical approach to the lateral cutaneous thigh nerve requires an incision between the trunk and the thigh root to be explored in its extra-pelvic and intra-pelvic portions.

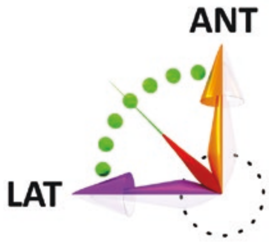
If it is a classic compression at 1 cm inside and below the anterior superior iliac spine, some authors propose an incision 3 cm below the inguinal fold, remaining parallel, in order to expose the nerve at the thigh only between the sartorius and the tensor fasciae latae muscles.

Nervous Exposure

Nerve exposure occurs through the incision of the fascia latae aponeurosis, allowing it to be released inside the tendon of the corresponding muscle and outside the sartorius. It is usually found in an aponeurotic tunnel, which is compressed, mainly by strangulation against the inguinal ligament. At times, the nerve splits early or conversely, which means that the incision must be enlarged downwards or upwards, making the vertical or oblique incision more convenient than the horizontal incision.

If an approach to the nerve requires exploration of the intra-pelvic portion, the femoral arch should be disinserted and the insertion of the large oblique of the iliac crest should be reflexed to follow the nerve against the anterior surface of the iliac muscle (Figure LFC12).

1- Anterior superior iliac spine
2- Fascia latae aponeurosis
3- Sartorius muscle
4- Lateral femoral cutaneous nerve



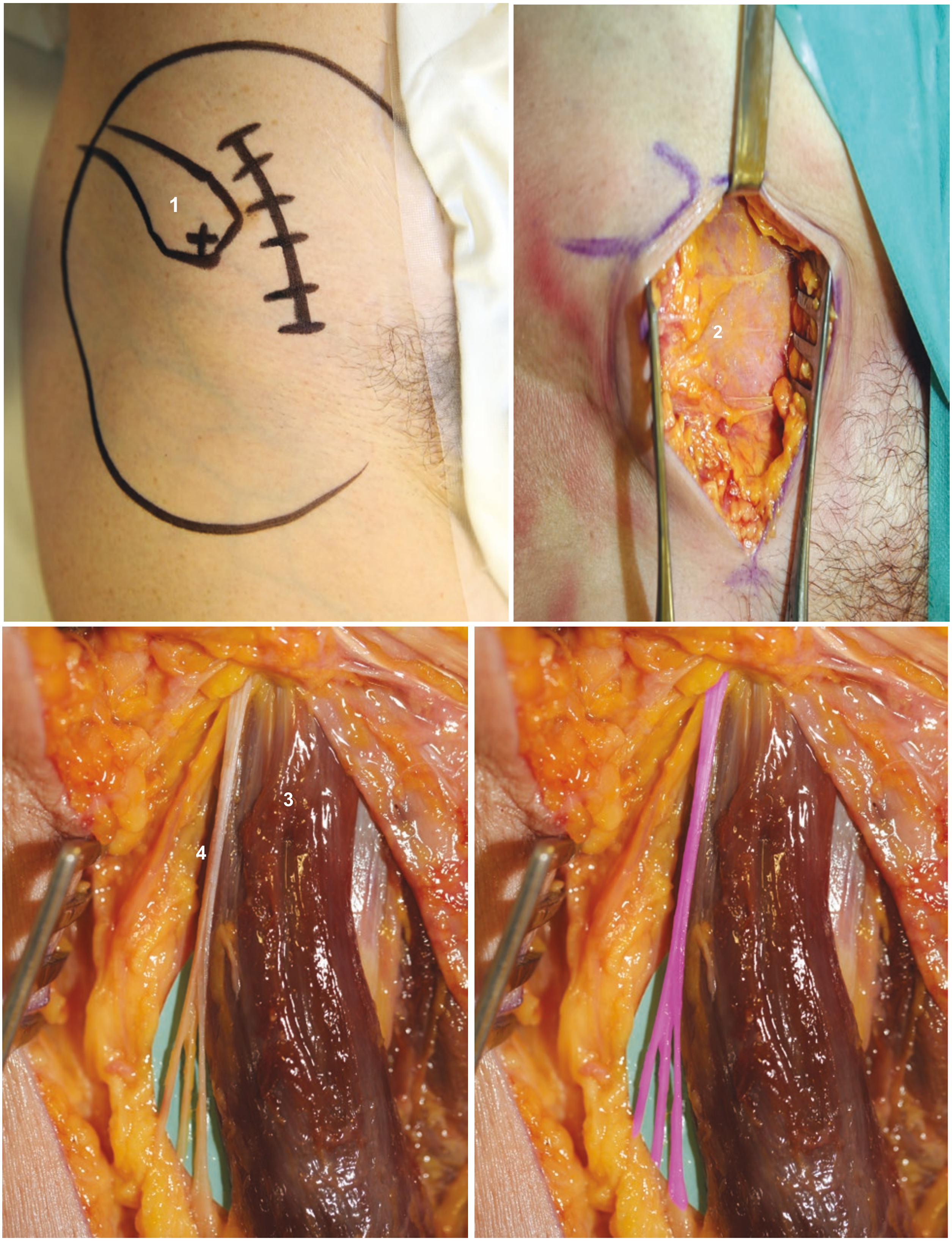
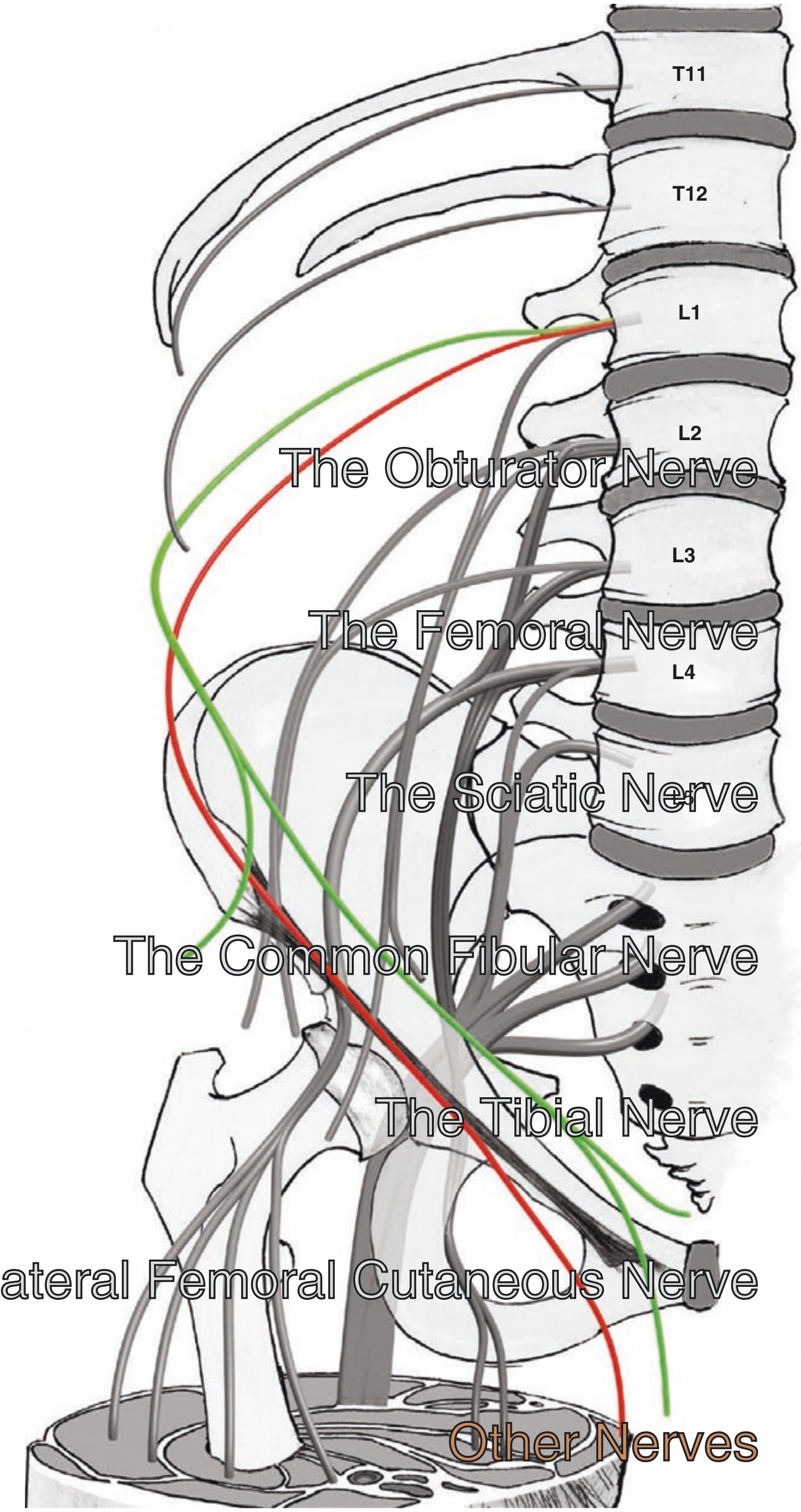


Figure LFC12. Surgical approach of the lateral femoral cutaneous nerve.



The Obturator Nerve

The Femoral Nerve

The Sciatic Nerve

The Common Fibular Nerve

The Tibial Nerve

The Lateral Femoral Cutaneous Nerve

Other Nerves

The Iliohypogastric Nerve

Morphological Data

The iliohypogastric nerve is a mixed nerve and a collateral branch of the lumbar plexus. It takes charge of the sensitive innervation of the external genitalia and of the superomedial face of the thigh. It also takes charge of the motor innervation of the inferior part of the abdominal wall.

Origin

The iliohypogastric nerve, a mixed nerve, comes from the L1 and also often from the T12 roots, above the ilioinguinal nerve (Figures I1 and I2a). It appears on the lateral border of the psoas.

Path

It goes through the quadratus lumborum and perforates the transverse muscle above the iliac crest just like the ilioinguinal nerve. At this level, it divides into two branches: the lateral and anterior branches (Figure I2).

Neurovascular Relations

The iliohypogastric nerve, at its origin, faces the lumbar artery from a distance and below. Since most of its path is superficial, there is no particularly noticeable relation with any vessel.

Collateral Branches

It gives off muscular ramifications for the muscles of the abdominal wall.

Terminal Branches

The lateral cutaneous branch goes through the two muscle layers formed by the internal and external oblique muscles and then spreads towards the lower part of the lateral abdominal wall and the upper part of the lateral face of the buttock (Figure I2).

The anterior cutaneous branch continues its way between the muscle layers, along the inguinal ligament. It becomes superficial by perforating the external oblique muscle, about 2.5 cm above the superficial inguinal ring. It innervates the hypogastric area and the adjacent part of the thigh at its superomedial face (Figure LFC5, chapter “The Lateral Cutaneous Nerve”).

Sensitive Function

There are many anatomical variations, and very frequently, the sensitive territories of these nerves overlap and assist each other; also, the ilioinguinal nerve’s diameter is often inversely proportional to that of the iliohypogastric nerve, situated below. There is variability from one subject to another and from one side to the other in an individual in 60% of cases.

Anastomoses

The iliohypogastric and ilioinguinal nerves generally make anastomoses with each other only.

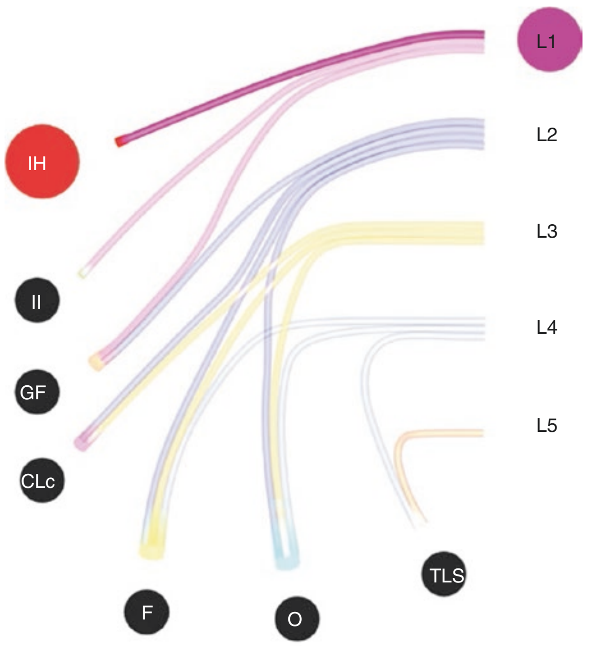


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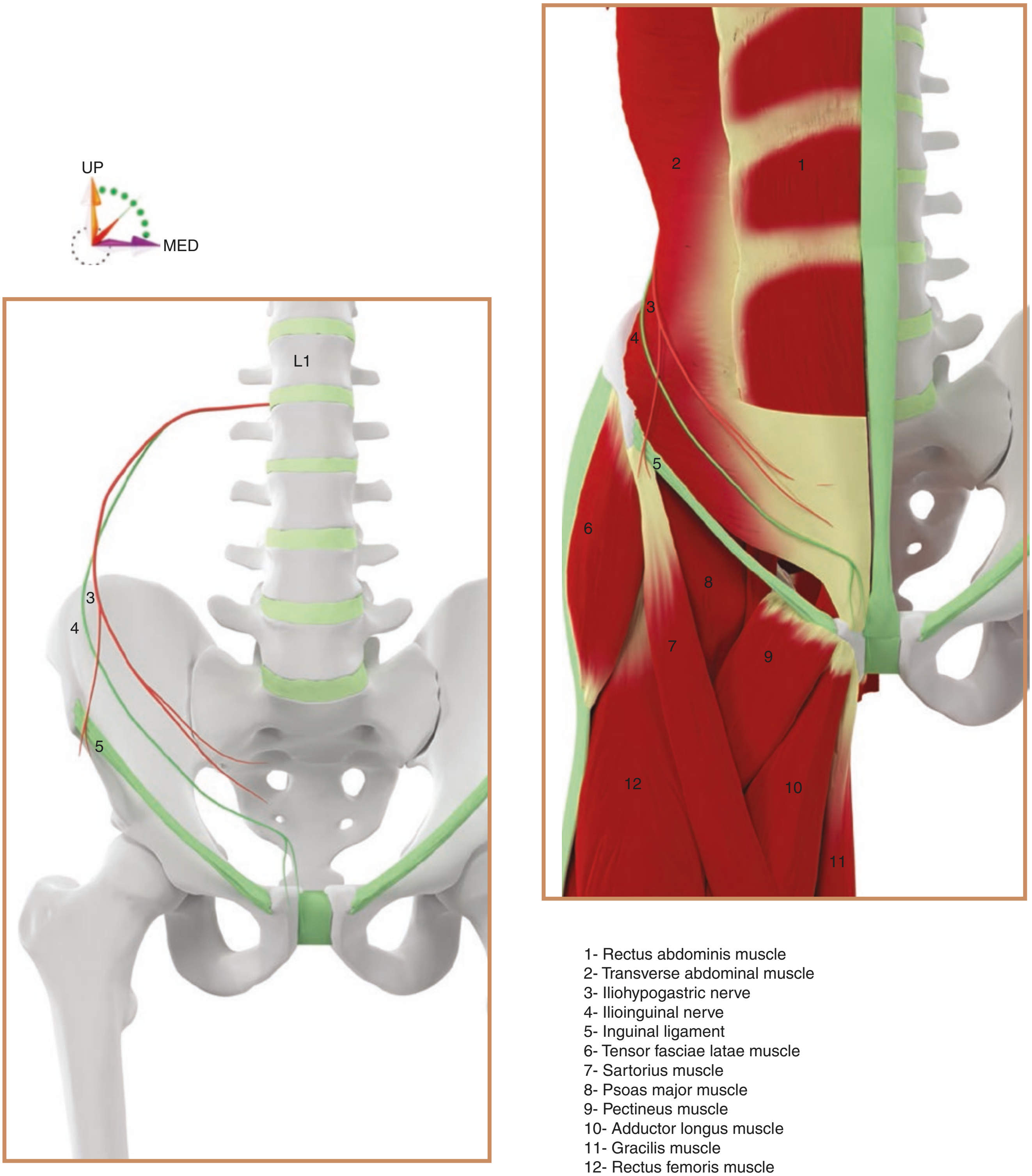
Figure I1. Origin of the iliohypogastric nerve.

Electronic Supplementary Material The online version of this chapter (https://doi.org/10.1007/978-3-030-49179-6_19) contains supplementary material, which is available to authorized users.



1- Rectus abdominis muscle
2- Transverse abdominal muscle
3- Iliohypogastric nerve
4- Ilioinguinal nerve
5- Inguinal ligament
6- Tensor fasciae latae muscle
7- Sartorius muscle
8- Psoas major muscle
9- Pectineus muscle
10- Adductor longus muscle
11- Gracilis muscle
12- Rectus femoris muscle

Figure I2. Topographical distribution of the iliohypogastric and ilioinguinal nerves and their relations with bones and muscles.

The Ilioinguinal Nerve

Morphological Data

The ilioinguinal nerve is a sensitive nerve which originates under the iliohypogastric nerve, with which it shares the same relations. It is a collateral branch of the lumbar plexus. It goes along the abdominal wall laterally and spreads towards the teguments of the hypogastric region.

Origin

The ilioinguinal nerve stems from the L1 root and goes under the iliohypogastric nerve in a subperitoneal way (Figures I3 and I4). It therefore shows the same path and same relations as this nerve.

Path

It appears on the lateral border of the psoas and goes through the transverse muscle near the anterior superior iliac spine (1 cm above it) and then goes through the internal oblique muscle (Figure I4). It gives off motor branches to these two muscles. Its path continues under the aponeurosis of the oblique muscle towards the pubis and pubic symphysis. It is then median to, below (less frequently) or outside of the spermatic cord in men or of the round ligament of the uterus in women. Still, it accompanies the spermatic cord, 2–4 cm below the superficial inguinal ring.

Neurovascular Relations

At its origin, the ilioinguinal nerve faces the iliohypogastric nerve and the lumbar artery from a distance and below.

Terminal Branches

The ilioinguinal nerve ends with two terminal branches, which are anterior and posterior.

Sensitive Function

This nerve takes charge of the sensibility of the superomedial part of the thigh, of the root of the penis and scrotum in men or of the mons pubis and labia majora in women (Figure LFC5, chapter "The Lateral Cutaneous Nerve").

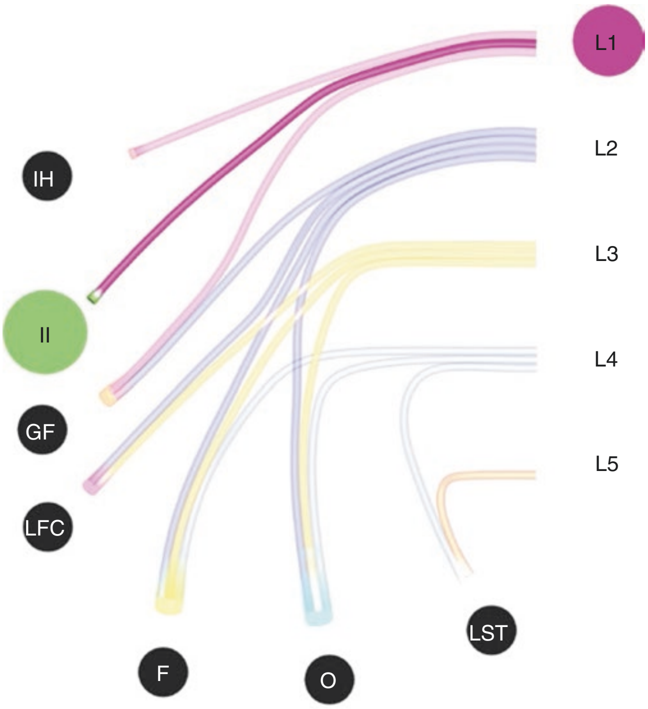
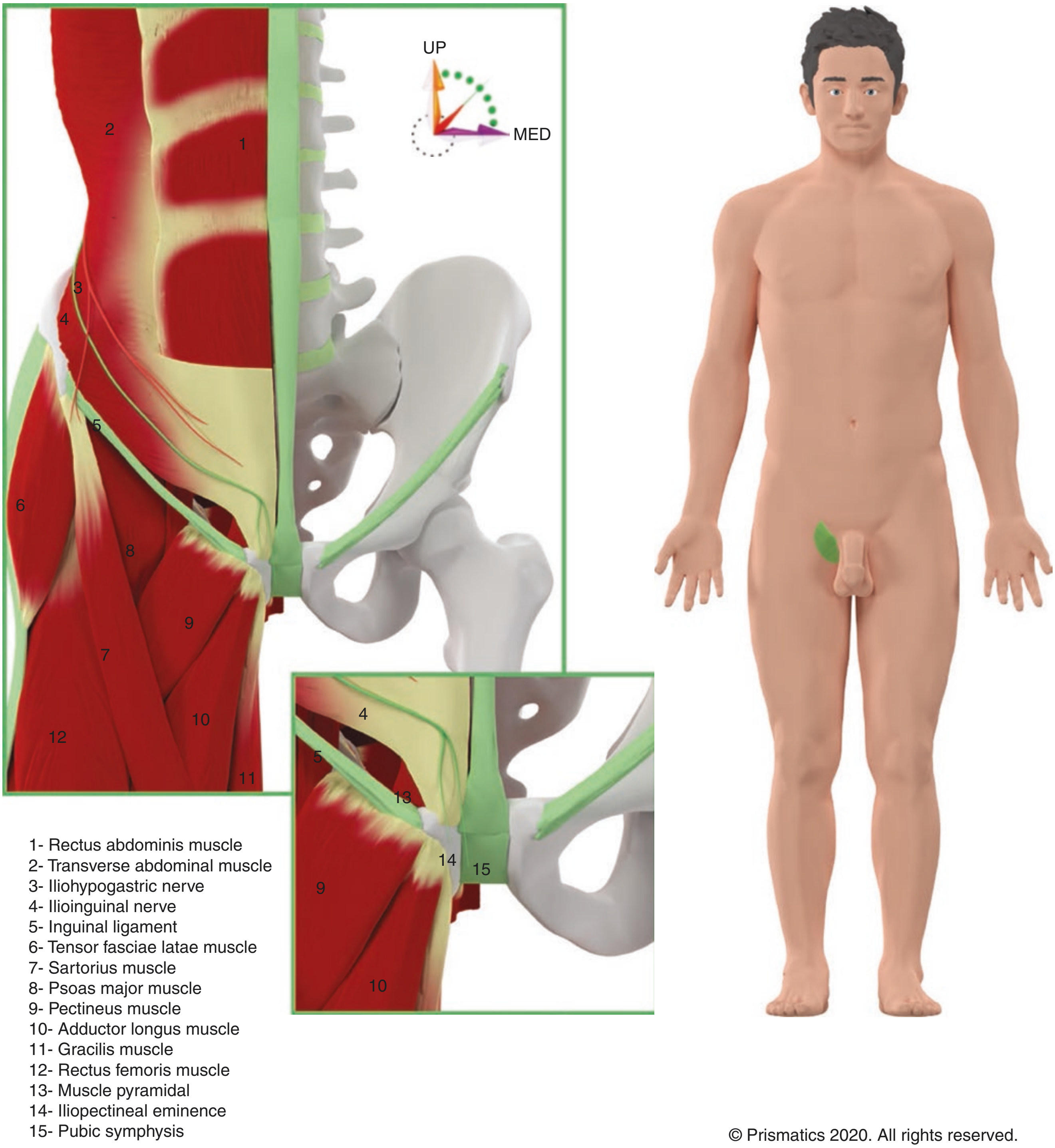


Figure I3. Origin of the ilioinguinal nerve.


UP
MED
1
2
3
4
5
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8
9
10
11
12
4
5
13
14
15
9
10
1- Rectus abdominis muscle
2- Transverse abdominal muscle
3- Iliohypogastric nerve
4- Ilioinguinal nerve
5- Inguinal ligament
6- Tensor fasciae latae muscle
7- Sartorius muscle
8- Psoas major muscle
9- Pectineus muscle
10- Adductor longus muscle
11- Gracilis muscle
12- Rectus femoris muscle
13- Muscle pyramidal
14- Iliopectineal eminence
15- Pubic symphysis

Figure I4. Muscular relations and sensitive innervation of the iliohypogastric and ilioinguinal nerves.

Pathology

Entrapment Neuropathies of the Ilioinguinal Nerve and of the Hypogastric Nerve

The ilioinguinal nerve is a sensitive collateral branch of the lumbar plexus. It goes laterally along the abdominal wall until the hypogastric region, innervating its wall.

The iliohypogastric nerve is a mixed collateral branch of the lumbar plexus. It innervates the skin of the external genitalia and the superior part of the medial face of the thigh.

Aetiology

These entrapment neuropathies are iatrogenic in most cases, especially after curing inguinal hernia, although they can also come as complications after appendectomy, urological interventions, iliac crest graft harvesting and gynaecological surgery (Figure I5).

A primitive nerve injury can be caused by a section, a compression, a stretching, a coagulation or a nerve contusion. A secondary injury of the nerve can come from a compression due to a scar, the formation of a schwannoma, an irritation caused by a stitch or a nearby granuloma.

Clinical Significance

- Sensitive signs: These signs appear as inguinal pain, felt by the patient as a continuous burning sensation, as opposed to paroxysmal. This pain increases when sitting, which induces a compression of the nerve when it goes through the oblique muscles, and when performing movements which cause a tension of the muscles of the abdominal wall. This pain can become paroxystic when coughing or sneezing. Patients often position themselves in such a way as to relieve the pain, in a position of coxa vara with an inclination of the body towards the painful side (Fig I5b).

  Sharp pains felt upon light, brushing touch would rather evoke the presence of a neuroma.

  An injury of the iliohypogastric nerve causes an inguinal pain and a pain felt in the inferomedial quarter of the abdomen, whilst an injury of the ilioinguinal nerve causes inguinal pain with irradiations towards the internal face of the thigh, the labia majora, the scrotum and the dorsal side of the penis (Figure LFC5, chapter “The Lateral Cutaneous Nerve”). Hyperpathia and/or hypoesthesia can accompany this pain. Chronic pelvic pain can also merge with these symptoms, especially in women.
- Motor signs: The iliohypogastric nerve innervates the muscular wall of the abdomen in a non-exclusive way. If it is injured, there will be no significant motor deficit.

Clinical Forms

A diagnosis of neuropathic pain can be given if pain in the area mentioned above lasts for more than 4 weeks after surgery in the inguinal region, or after surgery with section of the transverse muscle such as a nephrectomy, hysterectomy or an infiltration to the ureter. For the femoral branch, an infiltration to the external iliac artery can also lead to this diagnosis. However, the pain can appear several weeks or several years after. The maximal frequency of this injury is found in the aftermath of healing an inguinal hernia.

Treatment

Infiltration is the first treatment option to be suggested.

The iliohypogastric nerve can be infiltrated when it crosses the iliac crest. The efficacy can be judged by the disappearance of spontaneous pain and pain triggered by pressing on the greater trochanter.

Surgical treatment, aimed at exploration or decompression of the nerve, is only recommended for refractory forms.

Even though recommended by some, an orchidectomy is not advised, as it only brings partial relief in 20% of cases and the onset of “phantom testicle” pain much more frequently.

Denervation of the spermatic cord brings relief in 75% of cases in previously published papers.

The ilioinguinal nerve is injured more often than the iliohypogastric nerve. There is often a long period of inertia between the apparition of the symptoms and their complex treatment: between 1 and 4 years according to relevant literature.

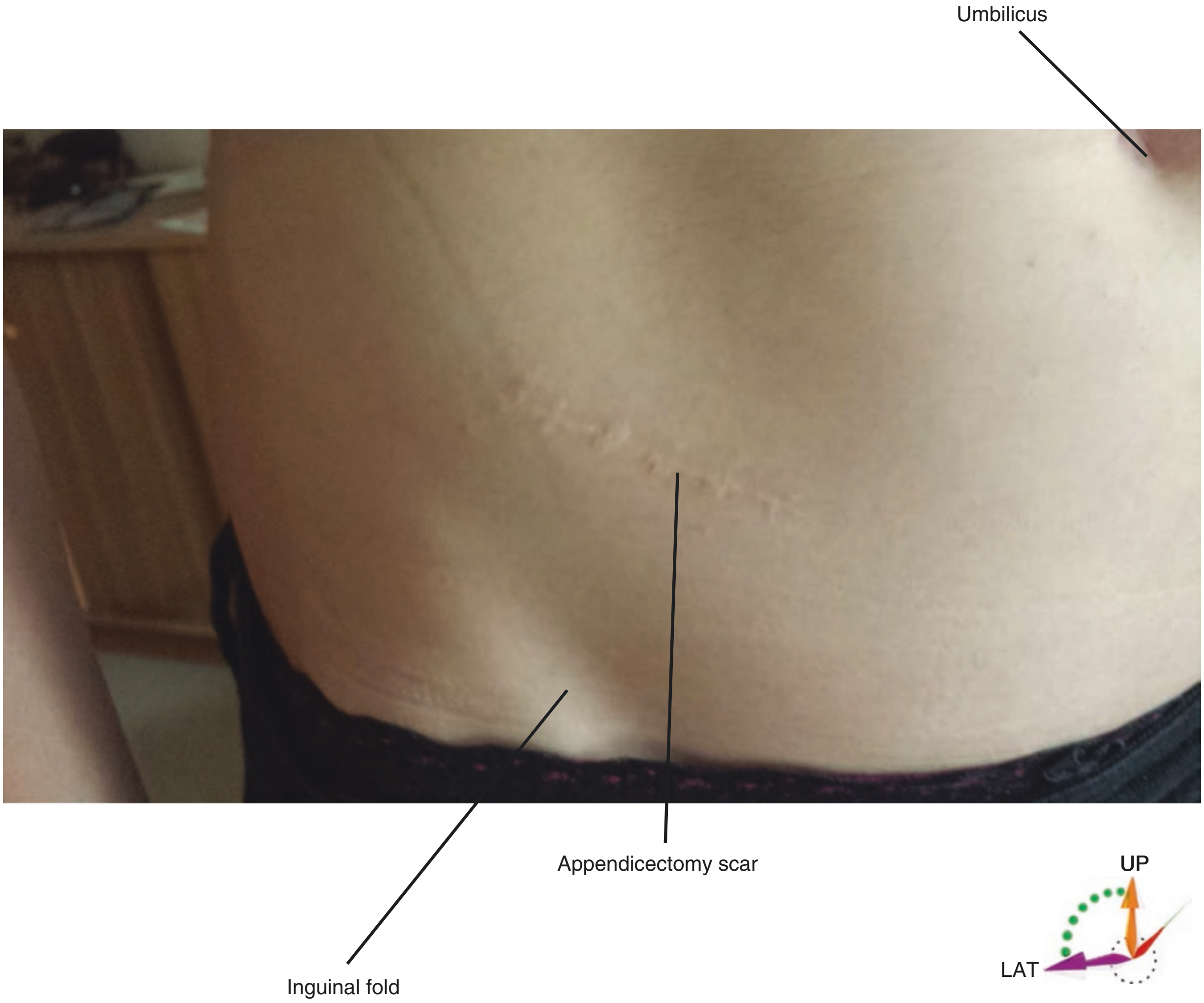
Umbilicus
Appendicectomy scar
Inguinal fold
UP
LAT

Figure I5. Case of a patient showing an ilioinguinal entrapment neuropathy linked to appendicectomy complications.

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INDEX

A
Abdominal external oblique muscle, 458
Abdominal internal oblique muscle, 458
Abductor digiti minimi muscles, 240, 382
Abductor hallucis muscle, 382
Abductor pollicis brevis muscle, 126, 190, 216
Abductor pollicis longus muscle, 126
Accessory cephalic vein, 94
Accessory obturator nerve, 290
Acetylcholine (ACh), 10, 12
  receptors, 12
Achilles reflex, 388
Achilles tendon, 400, 404, 406
Acromioclavicular joint, 58, 244, 247
Adductor brevis muscles, 282, 290, 298, 304
Adductor canal, 316, 330, 334
Adductor digiti minimi, 218
Adductor hallucis muscle, 382
Adductor longus muscles, 290, 304
Adductor magnus muscles, 298, 316, 342, 348
Adductor pollicis muscle, 126, 206, 218
Alar lamina, 24
Anastomosis, 94, 164, 176, 268, 282, 382, 410, 416
Anterior and medial femoral cutaneous nerves, 316
Anterior branch of obturator nerve, 304
Anterior cutaneous nerve of thigh, 316
Anterior interosseous artery, 154, 188
Anterior interosseous nerve, 164, 174
Anterior superior iliac spine, 338, 440, 449, 454, 460
Anterior tibial artery, 410, 416
Anterior tubercle of C4's transverse process, 48
Anterior tubercle of C6, 48
Anteromedial intermuscular septum, 120
Aponeurotic layer, 310
Arcade of Frohse, 126, 136
Arcade of Struthers, 216
Ascending lumbar artery, 282
Axillary artery, 40, 42, 44, 66, 76, 78, 84, 88, 94, 106, 115, 120, 138, 140, 146, 154, 178, 179, 182, 196, 206, 220, 250, 252
Axillary nerve, 66, 74, 76, 78, 82, 84, 120, 126
Axillary pit, 44, 164, 256
Axillary vein, 154, 196, 206
Axon, 2, 4, 6, 12, 13, 18, 20, 24
Axonal flow, 4–6, 20
Axonal regeneration, 20
Axonal sprouting, 18–20
Axonotmesis, 14

B
Band of Büngner, 20
Basal lamina, 10, 24
Basilic vein, 186, 206, 222
Biceps brachii muscle, 88, 94, 106, 112, 113, 178, 180, 186, 220
Biceps femoris muscle(Long head), 342, 348, 359, 365, 369, 374, 392, 404, 410, 424, 436
Botulinum toxin injections, 113
Brachial artery, 94, 115, 120, 154, 164, 178, 179, 196, 206, 220, 222, 224
Brachial canal, 14, 142, 196, 236
Brachial muscle, 88, 94
  biceps brachii, 88, 94
Brachial plexus, 32, 40, 42–48, 54, 56, 58, 59, 66, 74, 76, 78, 82, 84, 88, 106, 113, 115, 120, 146, 154, 196, 220, 234, 244, 256
Brachial tunnel, 154
Brachialis muscle, 32, 94, 106, 120, 148, 154
Brachioradialis muscle, 88, 120, 126, 140, 144, 148, 150, 188

C
Calcaneal branch, 382
Calcaneal tendon, 374, 382, 392, 398, 400
Calcaneus, 374, 392
Carpal tunnel syndrome, 154, 164, 174–176, 181, 184, 188, 190, 390
Cephalic vein, 94, 115
Chassaignac tubercle, 48
Clavicle, 40, 42, 44, 84, 244, 247, 249, 250, 256, 259
Common fibular nerve, 342, 348, 357, 359, 410, 422, 424–426
Common iliac artery, 282
Common palmar digital arteries, 206
Coracobrachialis muscle, 88, 94, 106, 112, 113, 115, 154, 186, 196
Coracoid process, 44, 88, 112, 115
Cricoid cartilage, 48
C4 root, 40
C5 root, 48, 54, 88, 113, 244
C6 root, 88, 113, 244
Cubital tunnel syndrome, 216, 218
Cutaneous nerve, 222, 452
Cytoskeleton, 4

D
Deep brachial artery, 118, 142, 148, 178
Deep branch of ulnar nerve, 206, 240
Deep circumflex iliac artery, 440
Deep circumflex iliac vessels, 338
Deep femoral artery, 316, 330
Deep palmar arch, 206, 240
Deltoid muscle, 66, 74, 76, 78, 84, 148, 244, 247
Deltopectoral groove, 84, 115
Dermatome, 26, 28, 30, 32
Dorsal branch of the ulnar nerve, 230
Dorsal digital nerves of the radial nerve, 164
Dorsal interossei muscles, 382
Dorsal root, 30, 234

Dorsal scapular nerve, 40, 54
Ductal fibular nerve syndrome, 436

E
Edema, 184
Embryological development, 24
Endoneurium, 2, 8
Epicondyle of the humerus, 88, 174
Epineurium, 2, 7, 8
Epitrochlear-olecranon groove, 196, 220, 222, 226, 236
Extensor carpi radialis brevis muscle, 126
Extensor carpi radialis longus muscle, 126, 136, 148
Extensor carpi ulnaris muscle, 136
Extensor digiti minimi muscle, 126
Extensor digitorum brevis muscle, 126
Extensor digitorum longus muscle, 426, 435
Extensor digitorum muscle, 126
Extensor hallucis longus muscle, 426
Extensor indicis muscle, 126
Extensor pollicis brevis muscle, 126
Extensor pollicis longus muscle, 126
Extensor retinaculum, 218, 416, 428, 430
External iliac artery, 282, 310, 440, 462
External iliac vessels, 440
External oblique muscle, 458

F
Fascia latae aponeurosis, 454
Femoral artery, 310, 316, 322, 324, 328, 330, 338 348, 440, 448
Femoral branch of the genitofemoral nerve, 310
Femoral canal, 310, 316
Femoral nerve, 268, 282, 290, 302, 304, 310–328, 338, 339, 444, 448
Femoral nerve syndrome, 322
Femoral neuralgia, 322
Femoral triangle, 282, 316
Femoral vein, 298, 330, 338
Fibula, 410, 424, 426, 433, 436
Fibular artery, 410
Fibular nerve, 14, 32, 357, 367, 369, 374, 382, 400, 410, 416, 422, 423, 425–427, 433, 434, 436, 437
  injury, 422
First and second lumbrical muscles, 206, 216
Flexor brevis digiti minimi, 382
Flexor carpi radialis muscle, 181, 188
Flexor carpi ulnaris muscle, 164, 196, 206, 216, 218, 220, 227, 228, 230, 231, 236, 238
Flexor digiti minimi brevis muscle, 206, 240, 382
Flexor digitorum brevis muscle, 396
Flexor digitorum longus muscle, 374, 382, 392, 404
Flexor digitorum profundus muscles, 180–182, 206, 216, 220, 227
Flexor digitorum superficialis muscle, 154, 174, 180, 181, 186, 188, 220, 238
Flexor hallucis longus muscle, 374, 382
Flexor pollicis brevis muscle, 164, 190
Flexor pollicis longus muscle, 174, 188
Flexor retinaculum, 164, 174, 196, 374, 382, 390, 392, 406
  of the hand, 154, 190

G
Genitofemoral nerve, 268, 316, 440, 444
Glenohumeral joint, 66, 76, 244
Glial cells, 2, 6
Gluteus maximus, 270, 342, 359, 365, 367, 369
Gluteus minimus, 270
Gracilis muscles, 290, 296, 316
Grape-picker palsy, 422
Great saphenous vein, 298, 316
Greater sciatic notch, 342, 359
Greater trochanter, 342, 359, 367, 444, 462
Groove of the psoas muscle, 310
Guyon’s canal, 176, 196, 220

H
Hamatum and pisiform bones, 218
Hamulus, 196, 206, 218
Homans’ sign, 388
Horner’s syndrome, 42
Humeral diaphysis, 146
Humeral groove, 120, 138, 148
Humeral head, 78, 82, 84
Hunter’s canal, 316
Hypothenar eminence, 206, 218

I
Iliac fascia, 310
Iliohypogastric nerve, 268, 458, 460, 462
Ilioinguinal nerves, 268, 458, 460, 462
Iliolumbar vein, 272
Iliopectineal arch, 310, 312, 338
Iliopsoas muscles, 268, 282, 310, 316, 322, 324
Inferior cluneal nerves, 270
Inferior gluteal artery, 342, 348, 359
Inferior gluteal nerve, 270
Inferior lateral cutaneous nerve of the arm, 126
Infrapatellar branch, 316, 333–335, 337
Infrapiriform foramen, 270
Infraspinatus muscle, 244, 247, 254
Infraspinous fossa, 244, 251
Inguinal ligament, 282, 310, 316, 440, 454, 458
Internal iliac artery, 348
Internal iliac vessels, 272, 342
Internal oblique muscle, 460
Internal obturator muscle, 282
Interosseous membrane, 126, 150, 164, 188, 374, 416
  of the forearm, 180
Inter-scalene triangle, 244
Inter-serrato-thoracic and inter-scapulo-thoracic spaces, 256
Ischial tuberosity, 342
Ischium, 359

K
Kiloh-Nevin syndrome, 174

L
Lateral axillary space, 66, 76, 78, 84
Lateral bicipital groove, 88, 106, 120, 140
Lateral branch of deep fibular nerve, 316, 410, 416, 424, 426, 428–431, 436
Lateral circumflex femoral artery, 310
Lateral cutaneous nerve of forearm, 88, 94, 106, 112
Lateral dorsal cutaneous nerve, 40, 74, 88, 94, 106, 112, 126, 140, 150, 206, 367, 369, 448
  of the foot, 348, 357, 382, 392, 396, 398, 402, 406, 410, 416, 422, 424, 426, 435
Lateral epicondyle, 94, 120
  of the humerus, 88, 112
Lateral femoral cutaneous nerve, 268, 310, 416, 440–447, 449–451, 453–455
Lateral head of gastrocnemius muscle, 348, 374, 392, 404, 410, 436
Lateral inferior genicular artery, 316, 330
Lateral intermuscular septum, 120, 148
Lateral malleolus, 400, 402, 416
Lateral palmar collateral nerve of the thumb, 164
Lateral palmar digital nerve of the middle finger, 126, 130, 164, 174, 206
Lateral palmar digital nerve of the ring finger, 164, 190
Lateral pectoral, 40
Lateral plantar nerve, 374, 382, 390, 406
Lateral proper palmar digital nerve of the index, 206
lateral sacral artery, 272
Lateral sural cutaneous nerves, 369, 382, 410, 436
Lateral thoracic artery, 256
Latissimus dorsi muscle, 78, 84, 106, 138, 178, 220
Levatorani muscle, 40
Levator scapulae, 40
Long muscle of the neck, 76, 78, 126, 196, 342, 365
Long thoracic nerve, 40, 54, 256–260
Lower axillary space, 120
Lumbar plexus, 268–270, 272, 274, 282, 296, 310, 322, 440, 446, 458, 460, 462
Lumbosacral plexus, 32, 268, 270, 275, 276
Lumbosacral trunk, 268, 270, 272, 342
Lumbrical muscles, 382
Lumbricals, 164, 206, 216, 382

M
Main branch, 206
Maisonneuve fractures, 422
Martin-Gruber anastomosis, 2, 164
Medial branch of the deep fibular nerve, 416, 431
Medial circumflex femoral artery, 282
Medial cutaneous nerve of arm, 40, 74, 128, 130, 154, 196, 206
Medial cutaneous nerve of forearm, 40, 126, 130, 154, 186, 196, 222
Medial cutaneous nerve of the thigh, 316
Medial dorsal cutaneous nerve, 24, 26, 416
  of the foot, 374
Medial epicondyle, 164, 174, 186, 196, 216, 226, 236
  of the humerus, 174, 216
Medial head of gastrocnemius muscle, 348, 374, 382, 392, 404
Medial inferior genicular artery, 316, 330
Medial intermuscular septum, 196, 206
Medial malleolus, 374, 382, 390, 392, 406, 422
Medial palmar digital nerve of the index, 126, 130, 164, 174
Medial palmar digital nerve of the middle finger, 126, 130, 164, 174
Medial pectoral, 40
Medial plantar nerve, 382
Medial sural cutaneous nerve, 369, 382, 404, 410
Median, 84, 106, 176, 181, 190, 206, 342, 348, 410, 424, 460
Median antebrachial vein, 154
Median nerve, 2, 14, 32, 40, 44, 94, 120, 130, 142, 154, 164, 174, 176, 179–182, 184, 186, 188, 190, 196, 206, 220, 222, 232, 236
  edema, 359, 404, 406
  neuroma, 190
Meralgia Paraesthetica, 446
Musculocutaneous nerve, 32, 40, 76, 88, 94, 106, 112, 113, 115, 120, 130, 154, 164, 206, 416
Musculoskeletal system, 10
Myelin, 6, 14, 16, 20, 24–26
Myelination, 2, 4, 6–7
Myotome, 24

N
Neck of the fibula, 412, 413, 416, 422, 423, 425
Nerve degeneration, 16–17
Nerve of the adductor magnus muscle, 348
Nerve of the semimembranosus muscle, 348
Nerve to the piriformis, 270
Nerve to the quadratusfemoris, 270
Neural repair, 18–20
Neuroma, 18, 190, 334, 462
Neuromuscular Junction, 10–12
Neuroplasticity, 20
Neurotmesis, 14
Node of Ranvier, 6
Nutrient artery of humerus, 94

O
Obturator externus muscle, 282, 290, 296, 298
Obturator internus muscle, 282, 342
Obturator internus nerve, 270
Obturator internus syndrome, 357
Obturator membrane, 282, 296
Obturator nerve, 268, 282–300, 302–307, 310, 316, 328
Obturator neuralgia, 296
Obturator neurovascular bundle, 78, 84, 88, 106, 282, 374, 416
Olecranon, 220
Omohyoid muscle, 42, 54, 244, 250, 252
Opponens digiti minimi, 206, 382
Opponens pollicis muscle, 164, 190, 216

P
Palmar interossei muscles, 206
Palmaris longus muscle, 176, 181, 190, 238
Patellar ligament, 218
Pectineus muscle, 282, 290, 296, 298, 304, 310, 316, 338
Pectoralis major muscle, 44
Perineurium, 2, 7, 8
Peroneal communicating branch, 410, 416
Peroneus brevis muscle, 416
Peroneus longus, 416
  muscle, 410, 416, 422, 426, 436
Phalen’s sign, 176
Phrenic nerve, 40, 48, 54, 56, 58
Piriformis muscle, 270, 342, 348, 357, 359, 365, 367
Piriformis syndrome, 357, 359
Pisiform bone, 196, 229, 230
Plantar interossei muscles, 382
Plantaris muscle, 382, 392
Plexus, 8, 24, 26, 28, 30, 32–34, 40, 42, 44, 48, 54, 56, 58, 66, 84, 244, 250, 252, 256, 270, 272, 282, 296, 310, 316, 322, 357, 359, 369, 440, 446, 458, 460, 462
Popliteal artery, 348, 374, 422
Popliteal fossa, 32, 270, 342, 346, 348, 357, 359, 363, 367, 369, 374, 378, 389, 392, 396, 404, 405, 410, 422, 436
Popliteal vein, 374
Popliteus muscle, 374, 382, 392, 404
Posterior branch of the obturator nerve, 282, 290
Posterior cervical triangle, 48
Posterior circumflex artery of the humerus, 66
Posterior cutaneous nerve of forearm, 140, 150
Posterior cutaneous nerve of the arm, 74, 126
Posterior cutaneous nerve of the thigh, 357
Posterior femoral cutaneous nerve (main branch), 154, 270, 342, 348, 382, 444
Posterior humeral circumflex artery, 66, 78
Posterior interosseous artery, 154, 188
Posterior interosseous nerve, 126, 136, 148
Posterior Interosseous nerve syndrome, 136, 148
Posterior tibial artery, 374, 382
Posterior tibial muscle, 382, 396, 404
Posterior tubercle of C4’s transverse process, 26, 32, 40, 48
Posterior tubercle of C6, 40, 48, 54, 58, 66, 82, 120, 146, 154, 247, 256
Posterior tubercle of C7, 40, 48, 54, 58, 120, 146, 154, 196, 234, 256
Pronator teres muscle (deep head), 150, 154, 164, 174, 180, 186, 188, 206
Psoas major muscle, 272
Psoas muscle, 268, 322, 338
Pubic symphysis, 460
Pudendal nerve, 357
Pudendal plexus, 270

Q
Quadratus femoris muscle, 357
Quadratus lumborum, 268, 440, 458
  muscle, 268
Quadratus plantae muscle, 382
Quadriceps femoris muscle, 316, 322, 440
Quadrilateral space, 76, 78, 84
  of Velpeau, 76

R
Radial artery, 120, 126, 140, 144, 154, 181
Radial nerve, 66, 74, 76, 88, 94, 120, 126, 130, 136, 138, 140, 142, 144, 146, 148, 150, 154, 164, 186, 206
Radial recurrent artery, 94, 120, 126, 150
Radius, 126, 143, 150
Rectus femoris muscle, 338
Recurrent thenar branch, 164
Rhomboid major and minor muscles, 40, 254
Riche-Cannieu anastomosis, 164, 206

S
Sacral plexus, 270, 271, 273, 276, 342, 357, 359
Sacroiliac joint, 270, 282, 342
Saphenous nerve, 290, 316, 330–336, 348, 416
Sartorius muscle, 304, 316, 330, 338, 440, 448
Scalene muscles, 40, 42
Scalenus anterior muscle, 42
Scalenus medius muscle, 42, 256
Scapula, 44, 84, 112, 244, 248, 249, 251, 254–256, 259, 260
Schwann cells, 2, 6–7, 14, 16, 18, 20, 24
Sciatic nerve, 32, 270, 302, 316, 342–370, 374, 410, 422
Seddon classification, 14
Semimembranosus muscle, 342, 359, 365, 374
Semitendinosus muscle, 342, 369, 374, 392, 404
Sensitive branch of the radial nerve, 146
Serratus anterior muscle, 40, 256
Small saphenous vein, 400
Soleus muscle, 374, 382, 388, 392
Soleus syndrome, 388
Spinoglenoid notch, 244, 251
Sternocleidomastoid muscle, 56, 58, 84
Subclavian artery, 42
Subclavian vein, 42
Subclavicular, 40, 84, 181
Subclavius muscle, 40, 42, 44
Subscapular artery, 206
Subscapularis muscle, 66, 78, 120, 154
Sunderland classification, 14
Superficial branch of the radial nerve joins, 120, 146, 164
Superficial fibular nerve, 410, 416, 424, 426, 432
Superficial palmar arch, 154, 206, 240
Superficial palmar branch of radial artery, 154, 206, 240
Superior and inferior gemellus muscles, 270
Superior and inferior nerves of the semitendinosus muscle, 348
Superior collateral ulnar artery, 216
Superior gemellus muscle, 342, 357
Superior gluteal artery, 272, 342, 348

Superior gluteal nerve, 270
Superior lateral cutaneous nerve of the arm, 66
Superior transverse scapular ligament, 247, 251, 252, 254
Superior ulnar collateral artery, 196, 206, 236
Supinator muscle, 126, 136, 140, 143, 150
Suprascapular artery, 244, 251, 252
Suprascapular nerve, 40, 48, 54, 76, 244–251, 253, 254
Suprascapular notch, 244, 247, 249, 251, 254
Supraspinatus muscle, 244, 251, 254
Sural nerve, 382, 388, 400–402, 416
Surgical neck of the humerus, 66, 78, 84
Synaptic vesicle, 4

T
Tarsal tunnel syndrome, 390, 398, 435
Tensor fasciae latae muscles, 448, 454
Teres major muscle, 76, 120, 140, 148
Teres minor muscle, 76, 78
Teres minor nerve, 66
Thenar branch of the median nerve, 164, 176
Thoracodorsal, 40
Tibia, 374, 392
Tibial artery, 392
Tibialis anterior muscle, 410, 416
Tibial nerve, 342, 348, 359, 374–388, 390–396, 398–400, 404–407, 410, 416
Tibiotarsal joint, 382
Tinel's sign, 176, 218, 388, 390, 422, 446
Transverse process of C5, 42, 48
Transverse scapular ligament, 244
Trapezius muscle, 58
Triceps brachii muscle, 78, 120, 126, 142, 148, 179, 196, 220, 224, 236, 254
Triceps surae muscle, 396, 424

U
Ulna, 143, 231
Ulnar artery, 2, 154, 196, 206, 216, 220, 224, 228–230, 232, 240
Ulnar canal, 196, 206, 218, 220, 229, 230, 232–234
Ulnar nerve, 32, 130, 154, 164, 181, 186, 196, 206, 216, 218, 220, 222, 227–230, 232–234, 236, 238
Ulnar tunnel syndrome (Guyon's Canal), 218
Upper and lower subscapular, 66

V
Vagus nerve, 32
Vasa nervorum, 2, 8
Vastoadductor intermuscular septum, 316
Ventral root, 32
Vertebral artery, 48

W
Wallerian degeneration, 16, 18